Mon. Not. R. astr. Soc. (1992) **259**, 121–145

The relation between abundance gradients and the physical properties of spiral galaxies

M. B. Vila-Costas and M. G. Edmunds
Department of Physics and Astronomy, University of Wales College of Cardiff, PO Box 913, Cardiff CF1 3TH

Accepted 1992 May 5. Received 1992 April 9; in original form 1991 October 22

SUMMARY

Some correlations of the behaviour of chemical abundance gradients with other physical properties of spiral galaxies are established. The sample is some 30 galaxies for which good published spectrophotometry of H II regions is available. The central abundances of spirals are correlated with their mass, barred galaxies have shallow gradients, and non-barred spirals show a correlation of gradient slope with morphological type. The correlation of abundance with mass surface density is confirmed and there are indications that the effective yield may vary as a function of metallicity.

Key words: galaxies: abundances – galaxies: fundamental parameters – galaxies: interstellar matter – galaxies: spiral.

1 INTRODUCTION

The study of abundances in H II regions in the discs of spiral galaxies has shown the existence of negative gradients with a higher abundance towards the centre of a galaxy (e.g. Pagel & Edmunds 1981; McCall 1982; Edmunds & Pagel 1984a; Evans 1986; Garnett & Shields 1987; Vilchez *et al.* 1988; Edmunds 1989; Díaz 1989; Shields 1990). The origin of these gradients is unclear (Pagel 1989), but various chemical models can produce them by radial variation in star formation rate and gas fraction (Pagel & Edmunds 1981; Edmunds & Pagel 1984a; Garnett & Shields 1987; Phillipps & Edmunds 1991), variable yield due to initial mass function (IMF) variations (Güsten & Mezger 1982), variation in the ratio of star formation rate to rate of inflow of unprocessed gas (Díaz & Tosi 1984), or radial flows of gas relative to stars (Edmunds & Greenhow 1992), perhaps arising from mismatch between the angular momentum of the disc and inflowing material (Mayor & Vigroux 1981; Lacey & Fall 1985; Pitts & Tayler 1989) or from viscous transfer (Clarke 1989; Sommer-Larsen & Yoshii 1989).

From the observational point of view, no clear correlation of the gradients with other properties of the galaxies (morphological type, total mass, magnitude, etc.) has been found. The only really positive result is the correlation found between the oxygen abundance and the surface density (Edmunds & Pagel 1984a; Garnett & Shields 1987). The fact that a similar correlation seems also to be present in elliptical (Edmunds & Phillipps 1989) and dwarf (Phillipps, Edmunds & Davies 1990) galaxies indicates its possible importance. There have been some indications of correlations of abundance with absolute magnitude (Garnett & Shields 1987) and cluster environment (Shields, Skillman & Kennicutt 1991), but it is not yet clear how these relations are affected by surface brightness selection effects in the samples.

The present study investigates possible correlations of physical parameters with the oxygen abundance for those galaxies with good spectral data available in the literature. The abundances were calculated in a consistent way. The purpose is to carry out a thorough study of possible correlations or trends that can be followed up with further observations until a clearer picture for the origin of the gradients emerges.

Section 2 gives the sources for the data used in the present study, Section 3 shows the main results of the various correlations investigated and Section 4 summarizes the conclusions.

2 DATA

The data for the present study of the discs of spiral galaxies of all morphological types (except Sa, for which no chemical data are available) have been taken from the literature.

2.1 Chemical data

A literature search for reasonably reliable H II region emission-line strengths in galaxies where more than one H II region along the disc had been observed was carried out. From the reddening-corrected line intensities given by the different authors the oxygen abundances [12 + log (O/H)] were obtained by the following methods. (i) The line ratio R_{23}, defined as

$$R_{23} = \log\{([\text{O II}]\lambda 3727 + [\text{O III}]\lambda\lambda 4959 + 5007)/\text{H}\beta\},$$

was calculated to give the oxygen abundance using the empirical strong-line method of Pagel *et al.* (1979), as recalibrated by Edmunds & Pagel (1984a), and adjusted at high and low abundance by Edmunds (1989) and Skillman (1989). (ii) For those galaxies where [O III] λ4363 (or any other temperature-sensitive line) was well measured, an estimate of the temperature and a value for the oxygen abundance were directly obtained, following the algorithm of McCall (1984) with the atomic data from Mendoza (1983). (iii) Finally, in a few cases where detailed H II region computer models had been carried out, we adopted the author's oxygen abundances.

The sources of the chemical data are given in Table 1.

2.2 Distance, inclination and position angle

The values found in the literature and those values adopted in the present study are given in Table 2. It can be seen that in some cases there are clear discrepancies between different authors.

2.3 Various scalelengths

The choice of the correct length-scale for a spiral galaxy disc is not obvious. To compare the gradients obtained when various normalizing radii are used we have checked several possibilities: the R_{25} radius – defined as the length of the major axis out to a blue surface brightness level of 25 mag arcsec^{-2}, corrected for inclination and galactic extinction; the effective aperture R_a – defined as the radius of the circular aperture which, when centred on the nucleus, contains half the total light of the galaxy [as given in the RC2 catalogue (de Vaucouleurs, de Vaucouleurs & Corwin 1976)]; the effective radius of the disc R_d – defined as the radius of the circular aperture which, when centred on the nucleus of the face-on galaxy, contains half the total light of the disc; and the effective radius of the spheroid R_{sp} – defined as the radius of the circular aperture which, when centred on the nucleus of the face-on galaxy, contains half the total light of the spheroid. For consistency, R_d and R_{sp} have been taken mainly from McCall (1982) and Simien & de Vaucouleurs (1986).

In most cases it is assumed that the spheroid component follows an $r^{1/4}$ brightness distribution and the disc an exponential profile (de Vaucouleurs & Pence 1978). The fitting of these two functions to the observed light distribution gives the four parameters R_d, Σ_d, R_{sp}, Σ_{sp}, where Σ_d (Σ_{sp}) is the surface brightness of the disc (spheroid) at radius R_d (R_{sp}). Such decompositions are not unique and an example of an alternative way to obtain the spheroid and disc contributions is given by Kent (1986). The decompositions into disc and spheroid by McCall compare reasonably well with those of Simien & de Vaucouleurs, although there are a few discrepancies (see Table 3). We have arbitrarily adopted the McCall value in such cases.

Finally, the radius for corotation R_c – defined as the radius at which the angular velocity of the spiral pattern is equal to the rotational angular velocity – has also been included for those few galaxies where it was available. These are obtained (except for NGC 628) from McCall (1982), but it should be noted that the determination of R_c is not very easy and more accurate values may eventually result from new methods [e.g. Cepa & Beckman (1990); their R_c for the only galaxy in common with this study, NGC 628, is the one given].

The scale-length parameters are given in Table 3.

2.4 Surface brightness and surface density

The surface brightness for a galaxy is directly obtained from the decomposition of its photometric profile into disc and spheroid components (Freeman 1970; Kormendy 1977; Boronson 1981; Kent 1985; Simien & de Vaucouleurs 1986; van der Kruit 1987). The distributions assumed follow

$$\mu_d = \mu_{e_d} + 1.822(r/r_d - 1), \quad \mu_{sp} = \mu_{e_{sp}} + 8.327[(r/r_{sp})^{1/4} - 1], \quad (1)$$

with μ_e as the surface brightness of the disc (μ_{e_d}) or the spheroid ($\mu_{e_{sp}}$) at the effective radius r_d, r_{sp} respectively.

To calculate a galaxy's mass surface density it is normally assumed that the mass distribution follows the light distribution with a constant mass-to-light (M/L) ratio. The rotation curve of the galaxy is used to fix this M/L ratio for the disc and the spheroid. Again for consistency the values obtained by McCall (1982) have been used where possible.

2.5 H I distribution

References for the H I distributions found in the literature are given in Table 1. The values used are all converted to face-on (zero inclination) and are given in $M_\odot$ pc^{-2}.

2.6 H_2 distribution from CO data

Table 1 gives the references for the CO distributions in the galaxies. To obtain the distribution of H_2 a constant conversion factor is normally assumed (Young 1990). However, there is evidence that this factor might not be constant between galaxies or within a galaxy (Maloney 1990). Indeed, there are theoretical arguments to suggest that the conversion factor could be a highly non-linear function of interstellar radiation field, density, chemical abundance, and mass spectrum of interstellar clouds (Maloney & Black 1988; Maloney 1990; Whitworth, private communication). We have investigated the effect both of using constant values [between the likely extremes of 0.8–4.8×10^{20} cm^{-2} (K km s^{-1})$^{-1}$, equivalent to 1.3–7.7 $M_\odot$ pc^{-2}] and of a dependence on metallicity. The results are discussed in Section 3.4.

The values used for the H_2 distributions are converted to face-on and given in $M_\odot$ pc^{-2}.

3 RESULTS

3.1 The gradient on various normalizing scales

The H II region abundances as a function of radius, separating morphological types, have been plotted, using R/R_{25}, R/R_d and R/R_{sp}, as given in Table 3. Fig. 1 shows the normalization to R_{25}. The origin of the scatter in abundances in a galaxy at a given radius is not completely clear. Undoubtedly much of it is spurious, caused by inaccuracies in the abundance determination method and observational errors. It is unlikely that significant variations in gas heavy element abundance do occur at a given radial distance, since mixing processes are probably efficient locally in annuli about the centre. We assume that scatter in any particular

Table 1. Literature sources for the chemical, CO and H I data of the galaxies in the present sample.

Galaxy name	Other name	Chemical data	CO data	HI data
NGC 55		1	(9).	37
NGC 224	M 31	2, 3, 4	1,2,3,4,(5),(6),(35),36	1,31,32,36
NGC 253		1	30,(37)	22,23,38
NGC 300		1, 5, 6, 7, 8		18
NGC 598	M 33	9, 10, 11, 12, 13,14	7, 38	2, 3
NGC 628	M 74	10, (29)		33
NGC 1313		15		
NGC 1365		5, 16	8	(4).
NGC 1566		(23).		
NGC 2403		10, 12	7	5, 6
NGC 2903		10, 12	(12).	
NGC 2997		6, 10		
NGC 3031	M 81	17,24	28,33	17,(11)
NGC 3184		10		
NGC 3344		10,18,19		33
NGC 3351		10		
NGC 4254	M 99	10,26	(10),11	
NGC 4303		26		
NGC 4321	M 100	10,26	7,11,(12)	
NGC 4395		10		33
NGC 4449		10	13	(4),(34)
NGC 4736		10	14	7,8
NGC 5055		10	(15).	7
NGC 5068		10		
NGC 5194	M 51	10,11,12, 25, (28)	16,17,18,19,(6),(20), (21),(31),(32),39	9,21,25,(26), 28,35
NGC 5236	M 83	1, (20), 21	7, 22, (6), (21)	(4),10,(24)
NGC 5457	M 101	10,11,12, 22, 30	23, (24)	6,12,13,35,(29)
NGC 6822		12,15	(34).	20
NGC 6946		10, (29)	17, 25, 26, 27,(37),(40)	6, 14, 15, 30
NGC 7424		(20).		
NGC 7793		1, 6, 10	(34).	27
IC 342		10	17, 25,(29),(40)	14, 16, 22

Columns are as follows. (1) Galaxy name. (2) Alternative name for the galaxy. (3) Sources for the chemical information. Their line strengths were used to obtain an oxygen abundance for the galaxies as described in the text. (4) Sources for the CO data. With an appropriate conversion factor these give the H_2 content along the disc of a galaxy. (5) Sources for the H I data.
Those references given in brackets have not been used in the present study because they do not include enough information, e.g. they give a total measurement for a galaxy. They may be useful in other studies. The photometric data and rotation curve decomposition have been taken from McCall (1982), McCall *et al.* (1985) or otherwise as indicated in the text. References for this table may be found in Appendix A.

galaxy is not intrinsic. None of the normalizing radii reduces the scatter *between* galaxies considerably and no clear dependence on morphological type is found. There is also no obvious reduction in scatter using R_c, but the sample is rather small in this case and values of R_c, as already mentioned, are very uncertain. The scatter is slightly reduced if the gradient as a function of R/R_d is normalized to the abundance value at R_d (Díaz 1989), but no other trend is observed. Fig. 2 shows the gradients for early (Sab–Sc) to late (Scd–Irr) type galaxies with the radius normalized to R_{25} and R_d. No obvious improvement is observed with either. Late-type galaxies tend to have lower abundances than early types, but with similar gradients.

It is important to notice the fact that the discs of most known spirals fit an exponential profile with a very similar central surface brightness ($\mu_0 = 21.7 \pm 0.4$ mag arcsec^{-2}; Freeman 1970; van der Kruit 1987). This implies that there is a relation between R_{25} and R_d with $R_{25}/R_d = 3.0 \pm 0.4$. In the present sample, therefore, these two parameters cannot be considered as independent and would be expected (as observed) to give similar results.

Nearly all the gradients are reasonably well fitted by a straight line of the form

$$12 + \log(\mathrm{O/H}) = a + b\,r, \qquad (2)$$

although in four cases (noted in Table 4) the slope appears to steepen in the central regions. To quantify the gradients we have simply taken an eye fit to the best straight line through the abundance points. An example is given in Fig. 3. The parameters of slope and central intersect are given in Table 4, with an indication of the quality of the data. The slope is given in dex arcmin^{-1} and in dex kpc^{-1} by using the distances given in Table 2. We believe that the extrapolated central intersect abundance is probably a better indicator of the element abundances in the central region than that obtained from nuclear spectra. This is because the nuclear spectra are strongly influenced by the nuclear ultraviolet and soft X-ray radiation fields and may give misleading results if

Table 2. Information on distance, inclination and position angle for the sample galaxies.

Galaxy name	Distance (Mpc)	Adopted Distance (Mpc)	Inclination (Deg)	Adopted Inclination (Deg)	P.A. (Deg)	Adopted P.A. (Deg)
NGC 55	2.3 (1), 1.4 (2), 1.6 (70,86)	2.0	85 (3,70), 80 (85),77 (87)	80	105 (3,70), 109 (85,87)	109
NGC 224	0.65 (4,15), 0.69 (5,6)	0.67	78 (8), 77.5 (6,7)	77	38 (8, 6)	38
NGC 253	2.5 (1,9,15), 2.6 (70)	2.5	78 (9), 73 (70)	78	51 (9,70)	51
NGC 300	1.9 (1), 2.0 (1,25,27), 1.79 (70) 1.53 (11),1.74 (12), 1.4 (13)	1.7	45 (14), 42.5 (10, 70)	43	108 (14), 109 (10), 106 (70)	108
NGC 598	0.72 (4,15,16,17), 0.82 (18,19)	0.72	54 (20,21), 55 (23), 57 (18,19,22,64)	55	20 (18,19,22), 21 (23) 22 (20,21,64)	22
NGC 628	7.21 (25), 8.17 (27)	7.21	4.0 (26)	4	36.0 (26)	36
NGC 1313	3.96 (25), 4.5 (3)	3.96	38 (28), 39 (29)	38	170 (28), 160 (30), 40 (3)	170
NGC 1365	9.91 (25), 20 (31,32),11.5 (45)	20	46 (33), 55 (34)	55	30 (31,81), 48 (34)	48
NGC 1566	6.79 (25), 15.3 (75)	6.79	30 (35)	30	50 (35)	50
NGC 2403	2.62 (36), 3.1 (18), 3.31 (19) 3.25 (37,38), 2.6 (39)	3.2	60 (40), 54 (18,19), 55 (41), 35 (42), 58 (39)	60	125.5 (40), 125 (18,19), 120 (42), 126 (39)	126
NGC 2903	7.52 (25), 6.67 (18)	7.52	72.0 (43), 70 (18)	72	28.0 (43), 33 (18)	28
NGC 2997	8.47 (25), 9.64 (45)	8.47	38.0 (44)	38	102.0 (44)	102
NGC 3031	3.1 (18), 3.47 (15), 3.25 (38,46), (47)	3.2	59 (18, 48)	59	152 (18, 48)	152
NGC 3184	7.62 (25)	7.62	24.0 (49)	24	159.0 (49)	159
NGC 3344	12.36 (25), 9.6 (50), (51)	12.4	21.0 (52)	21	140.0 (53)	140
NGC 3351	10.96 (25), 12.08 (45)	10.96	40.0 (54)	40	15.0 (54)	15
NGC 4254	12.53 (25), 12.76 (45)	12.53	29.0 (49), 28 (83)	29	58 (49),45 (83)	58
NGC 4303	12.94 (45)					
NGC 4321	11.43 (25), 12.13 (45), 20 (56)	11.43	35.0 (55), 28 (83)	35	155 (56), 120 (83)	155
NGC 4395	1.85 (25)	1.85	0 (25)	0	0 (25)	0
NGC 4449	4.25 (25), 5.4 (82)	4.25	30 (57)	30	50 (25)	50
NGC 4736	6.43 (25),6 (58),7.21 (45)	6.43	35 (58)	35	122 (58)	122
NGC 5055	6.82 (25), 6.31 (45)	6.82	55 (59)	55	99 (59)	99
NGC 5068	5.45 (25)	5.45	0 (49)	0	0 (49)	0
NGC 5194	7.87 (25), 6.9 (18), 6.5 (19), 9.7 (60)	7.9	35 (18,19), 20 (61)	20	0 (18,19), 170 (61)	170
NGC 5236	3.82 (25), 3.7 (1),8.9 (62), 7.9 (60), 4.21 (45)	3.8	24 (63,29)	24	45 (29,49,63)	45
NGC 5457	4.06 (25),4.1 (39), 74 (60,65), 5.6 (66), 5.01 (15), 6.9 (18), 6.5 (19), 6.92 (13)	4.1	17 (39), 27 (65,18,19) 18 (67), 22(68), 18 (69)	17	35 (39), 30 (18,19,65) 38 (67), 35 (68), 39 (69)	35
NGC 6822	0.41 (78), 0.44 (79)	0.41	69 (80), 21 (29)	69	125 (80)	125
NGC 6946	5.92 (25), 7.08 (15), 10.1 (18,60)	5.9	30 (71), 31 (18)	30	62 (71)	62
NGC 7424	9.08 (45)					
NGC 7793	3.4 (25,70), 2.51 (27), 3.2 (1)	3.4	53 (72,73), 57 (70)	55	108 (72, 73), 99 (70)	100
IC 342	2.72 (25), 2.94 (15), 4.5 (60,71,74)	2.7	25 (71,76)	25	39 (76), 40 (71)	40

Columns are as follows. (1) Galaxy name. (2) Various distance values in Mpc, with the corresponding reference given in brackets. (3) Adopted distances for the galaxies in Mpc. (4) Values for the inclination, with the corresponding reference in brackets. (5) Adopted inclinations for the galaxies. (6) Values for the position angle, with the corresponding reference in brackets. (7) Adopted position angles for the galaxies. References for this table may be found in Appendix B.

not analysed with great care (Edmunds & Pagel 1982, 1984b; Phillips *et al.* 1984). We have chosen not to attempt an impersonal fitting method for the gradient (e.g. least squares), not only because it is not obvious what fitting method would be most appropriate (least squares would be too influenced by spurious deviant points), but also because we do not wish to give a false sense of respectability to data which are not, at present, accurate enough to support more than a rough indication of correlation trends.

When the values of the gradients are plotted as a function of morphological type, no clear correlation is observed. However if the galaxies are separated (Fig. 4) into barred or non-barred classes, it is apparent that the barred galaxies have only very small gradients (although we accept that our sample – five galaxies – is small). The gradients for non-barred galaxies are steeper, and there is a correlation of gradient (expressed in dex kpc^{-1}) with morphological type, the later types having steeper gradients. The correlation is not nearly so marked for other radial normalizations and not apparent for mixed (barred/non-barred) types. Part of the correlation might be due to R_{25} and morphological type being related (Fig. 4c–d). A comparison of Figs 4(a) and (b) suggests that the processes producing the abundance gradients could be the same for both large and small spirals, with the variation in size giving the apparent correlation in Fig. 4(a). A correlation also exists with the metallicity in the centre of a galaxy, as extrapolated from the gradient, with early-type galaxies having a higher central abundance than late-type ones (Fig. 5a). This is true for both barred and non-barred galaxies. A correlation is found between the central

Table 3. Scalelength parameters, absolute magnitude and $B-V$ colour for the galaxies in the present sample.

Galaxy name	Type	R25 (arcmin)	Ra (arcmin)	Rd (arcmin)	Rsp (arcmin)	Ref	Rc (arcmin)	Mb	B-V
NGC 55	.SBS9*/	11.45						-19.0	
NGC 224	.SAS3..	77.44	25.06	38.98,38.90	17.56,17.50	1,2	69.80	-20.6	0.74
NGC 253	.SXS5..	9.75	3.54	5.40	7.65	2		-19.7	0.82
NGC 300	.SAS7..	9.75		4.81,4.80	0.50	1,2		-17.6	
NGC 598	.SAS6..	28.77	13.15	12.17,12.10,14.40	2.77,2.75,2.32	1,2	25.30	-18.4	0.44
NGC 628	.SAS5..	5.36	2.62	2.40	0.43	1,2	2.35*	-19.7	0.51
NGC 1313	.SBS7..	4.16		1.80	0.07	1,2		-18.7	
NGC 1365	.SBS3..	4.46	1.77	1.22	0.22	1,2		-21.6	0.51
NGC 1566	.SXS4..	3.88	1.12	1.89,1.61	0.50,0.48	1,2*		-19.0	0.76
NGC 2403	.SXS6..	8.49	3.15	2.73		1	4.99	-19.1	0.37
NGC 2903	.SXT4..	5.61	1.55				2.33	-20.3	0.53
NGC 2997	.SXT5..	4.35	1.58	2.35	0.31	1,2*		-19.7	
NGC 3031	.SAS2..	11.99	3.54	4.70,4.85	1.90,0.69	2		-20.1	0.81
NGC 3184	.SXT6..	3.62						-19.0	0.60
NGC 3344	RSXR4..	3.54						-20.0	0.50
NGC 3351	.SBR3..	3.62	1.15	0.96		1		-19.9	0.71
NGC 4254	.SAS5..	2.75	1.09	1.06		1		-20.2	0.51
NGC 4303	.SXT4..	3.08	1.12					-20.4	0.48
NGC 4321	.SXS4..	3.54	1.86	1.65	1.90	1		-20.3	0.67
NGC 4395	.SAS9*.	6.29						-15.7	0.48
NGC 4449	.IB.9..	2.45	0.97					-18.4	0.33
NGC 4736	RSAR2..	5.48	0.79	1.00	0.52,0.32	1,2		-20.2	0.69
NGC 5055	.SAT4..	5.74	1.77	2.38	0.36	1,2*	3.07	-20.0	0.64
NGC 5068	.SXT6..	3.54						-18.5	
NGC 5194	.SAS4P.	5.24	1.99	2.60	3.00	1	3.89	-20.8	0.52
NGC 5236	.SXS5..	5.87		3.95,2.02	0.31,0.13	1,2	3.42	-19.9	
NGC 5457	.SXT6..	14.09	5.61	3.28		1	7.79	-19.9	0.40
NGC 6822	.IBS9..	5.48		4.86		1		-14.4	
NGC 6946	.SXT6..	6.59	2.51	3.62,3.07	1.33,0.17	1,2*	4.18	-20.9	0.54
NGC 7424	.SXT6..	3.88		2.21,2.58	0.40,0.31	2		-19.0	
NGC 7793	.SAS8..	4.35	1.58	2.24,1.85	0.10,0.20	1,2*		-18.1	0.51
IC 342	.SXT6..	11.19	7.06	6.99,8.03	0.13,0.09	1,2*	15.17	-20.8	

Columns are as follows. (1) Galaxy name. (2) Morphological type from de Vaucouleurs *et al.* (1976, RC2). The letter in the third position indicates non-barred (A), barred (B) or mixed (barred/non-barred) galaxies. The morphological type, T, is given by the number in the fifth position. R_{25} in arcmin, from RC2. (3) Apparent radius, R_a, in arcmin, from RC2. (4) The scalelength of the disc. (5) The scalelength of the spheroid. (6) References for R_d and R_{sp}. These come from either McCall (1985), indicated by 1, or Simien & de Vaucouleurs (1986), indicated by 2. The first value given is from McCall. Any further values are from Simien & de Vaucouleurs. 2* indicates that the first value is a value common to both sources. (7) Radius of corotation taken from McCall (1982) or McCall *et al.* (1985). The value for NGC 628 comes from Cepa & Beckman (1990). (8) Absolute magnitude (M_b) obtained by taking the apparent blue magnitude from Tully (1988) and the distance adopted for the galaxies in the study, according to Table 2. (9) ($B-V$) colour for the galaxies in the sample, taken from RC2.

metallicity and the central surface *density* of the disc (Fig. 5b). The disc central surface density is also correlated with morphological type (Fig. 5c). No correlation is found, however, with the disc central surface *brightness*, which has a value around 21.5 for all the galaxies in the sample. No correlation is found with either the spheroid central surface brightness or its density. None of the central surface density or brightness parameters correlates with the gradient in metallicity. This is not improved by dividing the sample into barred and non-barred galaxies, but an increase in the sample would be desirable.

3.2 The gradient as a function of surface brightness along the disc

For most of the sample the values for the decomposition into a disc and spheroid component given by McCall (1982) have been adopted. The sample is divided into early (Sa–Sc) and late (Scd–Irr) types and the effect of using just the disc, the spheroid or total surface brightness is investigated. Fig. 6 shows the results of plotting the individual H II region abundances against the surface brightness at that radius. A correlation between the metallicity and the surface brightness along radius is found but the scatter is quite large. The best fit is obtained when the surface brightness of the *spheroid* alone is used. This could be partly due to the fact that spheroids of late-type galaxies tend to be less bright than those of early types.

When the sample is separated into barred and non-barred galaxies, no difference is found for the early-type galaxies. However, for late-type galaxies, the discs of the non-barred ones appear brighter than those of the barred ones, which have a similar brightness to those of early-type galaxies.

3.3 The gradient as a function of surface density

The values obtained by McCall (1982) are again adopted, and the differences between late- and early-type galaxies are investigated, as well as the effect of using only the disc or the spheroid in the decomposition. For late-type spirals no bulge is normally detected. For early-type galaxies, less scatter is observed in the correlation when the *total* (disc and bulge) surface density is used. Fig. 7 shows the results for early- and late-type spirals. The correlation is very good, as already

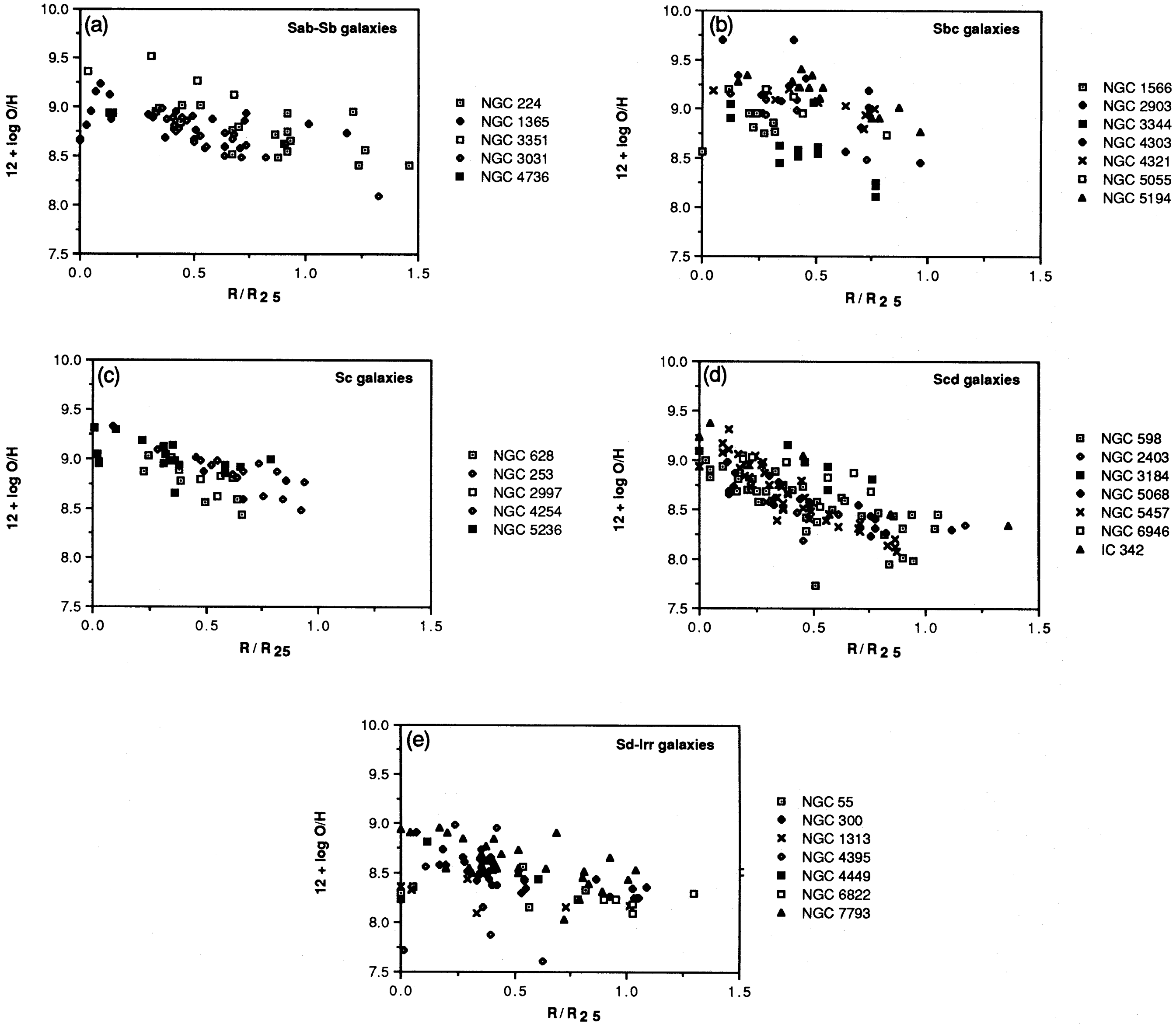

Figure 1. Oxygen abundance gradients for the galaxies in the sample for different morphological types. The radius has been normalized to R_{25}.

indicated by Edmunds & Pagel (1984a). No obvious dependence on morphological type – including the presence or absence of a bar – is observed, except for the effect of late types showing H II regions at lower surface densities.

3.4 Metallicity as function of gas fraction: yields

For eight of the galaxies (NGC 224 = M31, NGC 598 = M33, NGC 2403, NGC 5194 = M51, NGC 5236 = M83, NGC 5457 = M101, NGC 6946, IC 342), enough information is available to attempt a calculation of the gas fractions and the chemical yields (see Section 3.4.2 below) along the disc. The decomposition of the rotation curves comes from the same author (McCall 1982; McCall, Rybski & Shields 1985). NGC 3031 (M81) can also be included, but the information on the rotation curve comes from Rots (1975). In the case of NGC 253 there are data on the gas distribution, but the only mass decomposition (Wang 1990) was obtained with rather different assumptions and it is not used in the present study.

3.4.1 The H I and H_2 distributions

Before using the H I and H_2 data to calculate the gas fractions in the galaxies, the two distributions can be compared. The H I appears normally as a peaked profile with a dip in the centre of a galaxy and a flatter distribution along the disc. The H_2 data, as obtained with a constant conversion factor from the CO distribution, show an exponential behaviour with a high value in the centre of a galaxy and decaying faster with radius than the H I. See Fig. 8 for some examples.

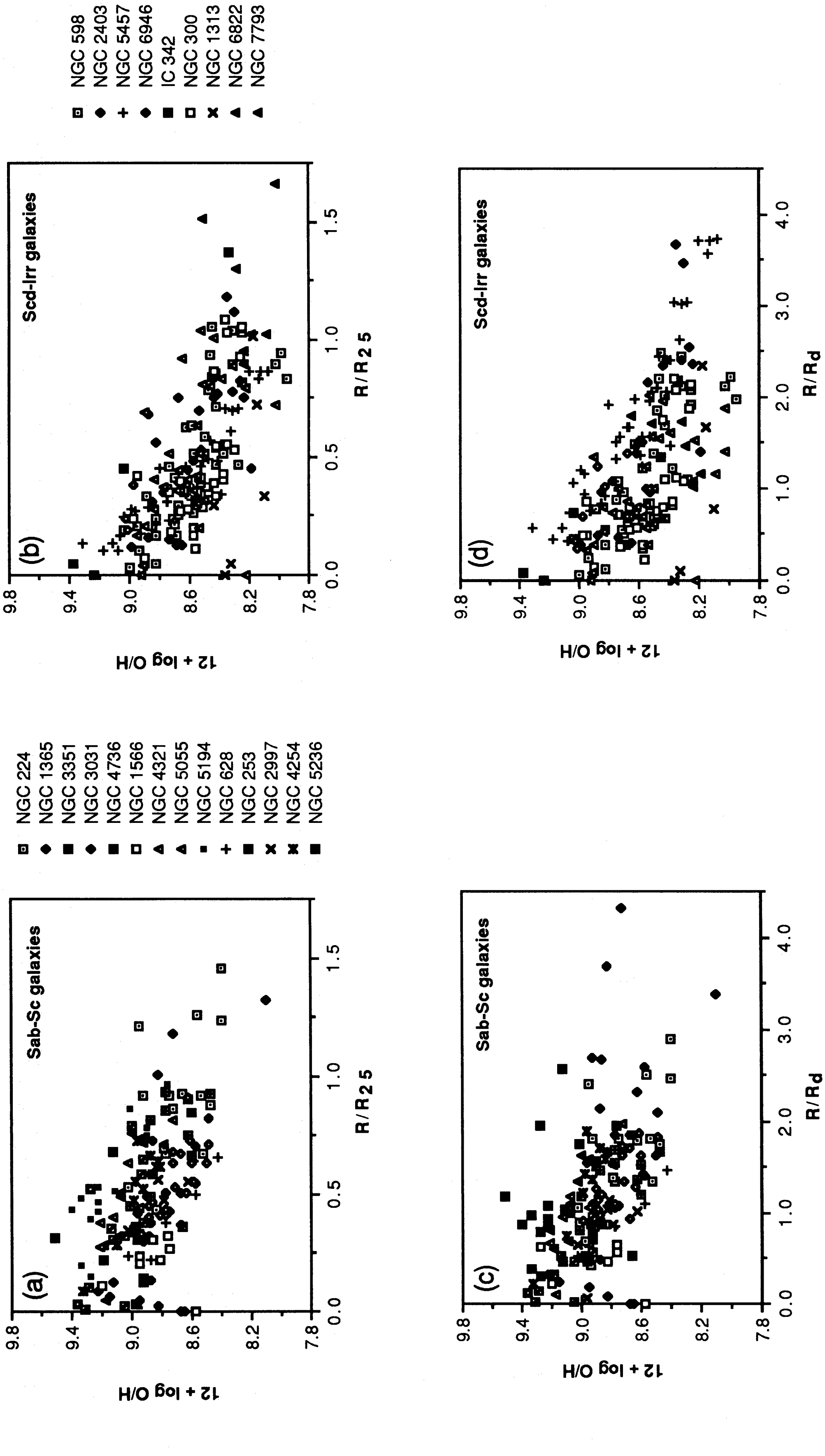

Figure 2. Comparison of the oxygen abundance gradients for early (Sab–Sc) and late (Scd–Irr) type galaxies, with the radius normalized to R_{25} and to R_d.

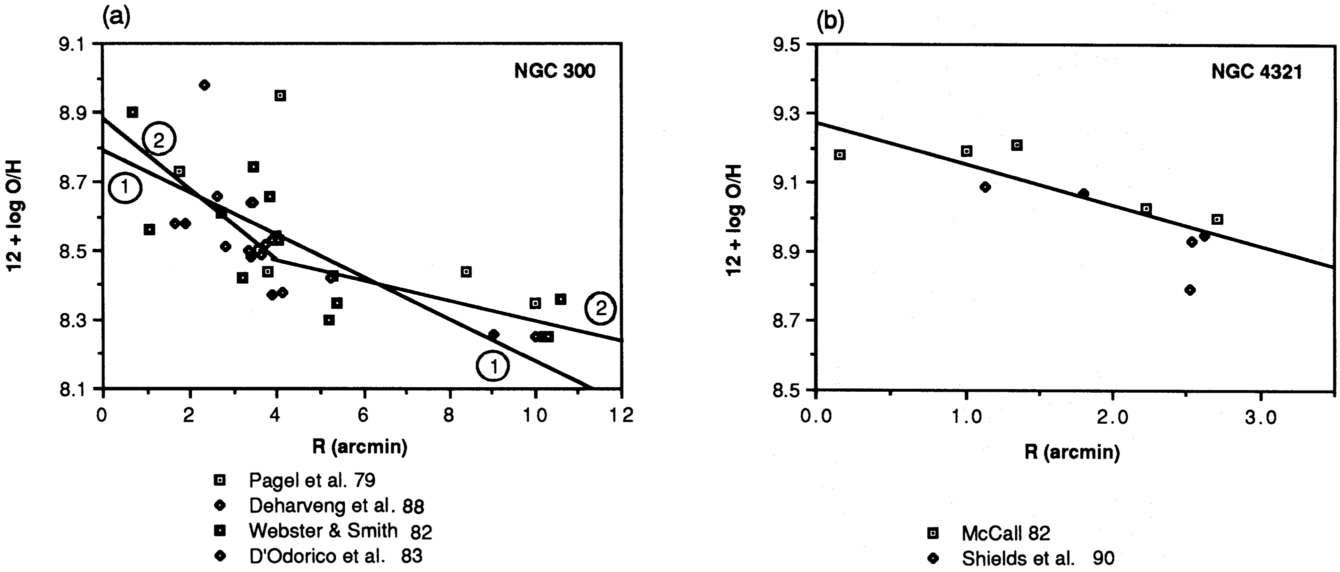

Figure 3. Example of the fit to the abundance gradients for (a) NGC 300 and (b) NGC 4321.

Table 4. Fits to the abundance gradients for the sample galaxies. Four of the galaxies show a variation in the slope of the gradient, so both fits are given.

Galaxy name	Slope (dex/arcmin)	Slope (dex/kpc)	Intersect (dex)	Quality	No. of HII regions
NGC 55	-0.015	-0.026	8.44	C	6
NGC 224	-0.0084	-0.043	9.25	A	19
NGC 253	-0.077	-0.11	9.32	B	9
NGC 300	-0.050	-0.10	8.78	A/B	37
	-0.092/-0.030	-0.19/-0.061	8.86/8.61		
NGC 598	-0.021	-0.10	8.94	A	37
NGC 628	-0.21	-0.10	9.25	A	7
NGC 1313	-0.054	-0.047	8.36	A	6
NGC 1365	-0.035	-0.006	8.97	B	19
NGC 1566					(8).
NGC 2403	-0.081	-0.087	8.86	B	16
NGC 2903	-0.18	-0.082	9.58	A	7
NGC 2997	-0.145	-0.059	9.15	B/C	6
NGC 3031	-0.075	-0.079	9.24	A	27
NGC 3184	-0.15	-0.069	9.22	C	6
NGC 3344	-0.36	-0.10	9.14	A	5
NGC 3351	-0.11	-0.034	9.44	C	4
NGC 4254	-0.26	-0.071	9.35	C	9
NGC 4303	-0.26	-0.073	9.27	C	9
NGC 4321	-0.12	-0.035	9.27	B/C	10
NGC 4395	-0.075	-0.14	7.96	B	4
NGC 4449					2
NGC 4736					2
NGC 5055	-0.156	-0.079	9.44	A	5
NGC 5068	-0.26	-0.17	8.97	B/C	4
NGC 5194	-0.14	-0.060	9.54	A	15
	0.0/-0.18	0.0/-0.080	9.33/9.75		
NGC 5236	-0.073	-0.066	9.24	B	17
NGC 5457	-0.124	-0.10	9.37	A	41
	-0.158/-0.053	-0.13/-0.044	9.48/8.79	A	
NGC 6822	-0.005	-0.042	8.24	A	7
NGC 6946	-0.07	-0.041	9.12	A	7
NGC 7424					(5).
NGC 7793	-0.168	-0.17	8.98	A/B	31
	-0.178/-0.065	-0.18/-0.066	8.98/8.68	A/B	
IC 342	-0.068	-0.087	9.3	A	5

Columns are as follows. (1) Galaxy name. (2) Fitted slope in dex arcmin^{-1}. (3) Fitted slope in dex kpc^{-1} with the adopted distance given in Table 2. (4) Central intersect of the fitted slope, in dex. (5) Quality indicator of the oxygen abundance data that give the fit. The best data are given by A and the worst by C. (6) Number of H II regions for which there are abundance determinations.

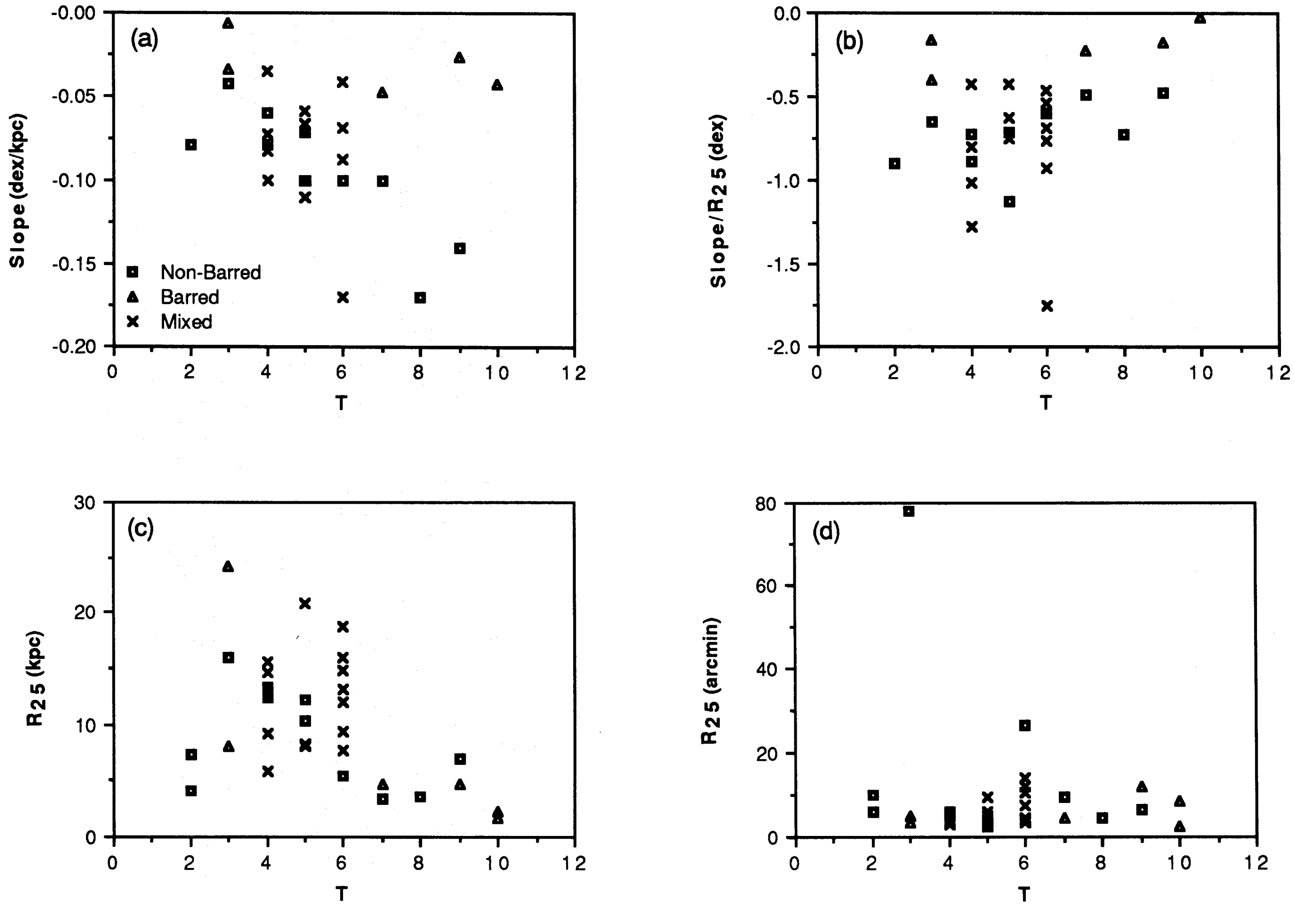

Figure 4. The gradient fitted to the oxygen abundance is plotted versus morphological type. Non-barred, barred and mixed galaxies are indicated by filled squares, open triangles and crosses respectively. A correlation for non-barred galaxies is seen when the gradient is given in dex kpc^{-1} (a). Nothing as clear is seen for the gradient normalized to R_{25} (b). A possible correlation between morphological type and R_{25} in arcmin or kpc is investigated in (c) and (d) respectively.

The use of a constant conversion factor is probably too simplistic, particularly towards the centres of galaxies where higher activity is present and for those galaxies with low metallicities (Maloney 1990). The effects of varying the constant factor between 0.8 and 4.8×10^{20} and of introducing a metallicity dependence – suggested to be $1/Z$ for values of $Z<Z_\odot$ – have been investigated. We hoped to find some characteristic form of the total (H I + H_2) distribution that could help to decide the issue. We have tried to find the conversion factor that would give the *total* gas distribution closest to an exponential, or at least give the smoothest total gas distribution as a function of radius.

Many of the galaxies have $Z>Z_\odot$ for the whole disc where H II regions have been observed. NGC 5194 (M51), NGC 5236 (M83) and NGC 6946 show $Z>Z_\odot$ for the whole galaxy; NGC 224 (M31), NGC 253 and IC 342 show $Z>Z_\odot$ at most radii; NGC 2403 shows $Z<Z_\odot$ for most of the galaxy; NGC 598 (M33), NGC 3031 (M81) and NGC 5457 (M101) change from $Z>Z_\odot$ to $Z<Z_\odot$ at an intermediate radius (see Table 5). The use of '$Z_\odot$' = 0.0132 (from H II regions) or '$Z_\odot$' = 0.0209 (from stars; Shaver *et al.* 1983) for the solar value does not affect the results very much. In Fig. 8 the various distributions are shown for the galaxies NGC 598 (M33) and NGC 5194 (M51). Unfortunately, no clear answer comes from the comparison of H I and H_2 distributions. In Table 5 the results are summarized for the various galaxies. No one conversion factor gives a smooth exponential total profile for all galaxies. The 'best'-fitting conversion factor for each galaxy is given.

Following the results of Tosi & Díaz (1990), we have plotted in Fig. 9 the oxygen abundance of individual H II regions versus the H_2 gas fraction ($\Sigma H_2/\Sigma$ Gas) for those galaxies where gas distribution information is available, and a correlation does indeed exist. We have used our 'best' conversion factor for the CO to H_2, but only a slight steepening of the correlation is found if any of the other conversion factors studied here is used. Our best fit is given by

$$\Sigma H_2/\Sigma \text{Gas} = 0.80[12+\log(O/H)] - 6.68, \quad (3a)$$

which is quite close to that obtained by Tosi & Díaz of

$$\Sigma H_2/\Sigma \text{Gas} = 0.37[12+\log(O/H)] - 2.99. \quad (3b)$$

The physical significance of this result is not clear and could have more to do with the molecular conversion factor than with the cycle of star formation and element synthesis. Indeed, Tosi & Díaz could not easily explain the behaviour by galactic chemical evolution models. The conversion of atomic hydrogen into molecular form is probably sensitive to

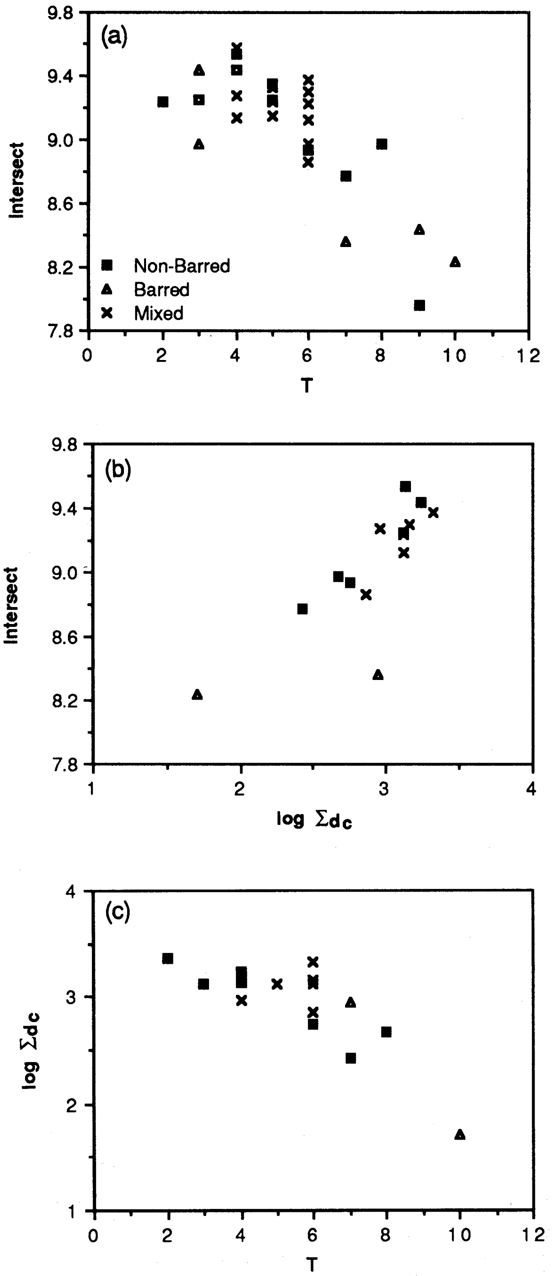

Figure 5. A correlation is found between the morphological type and the central intersect extrapolated from the slopes fitted to the oxygen gradient (a) and between this central intersect and the disc central surface density (b). These two parameters (morphological type and disc central surface density) are also correlated (c).

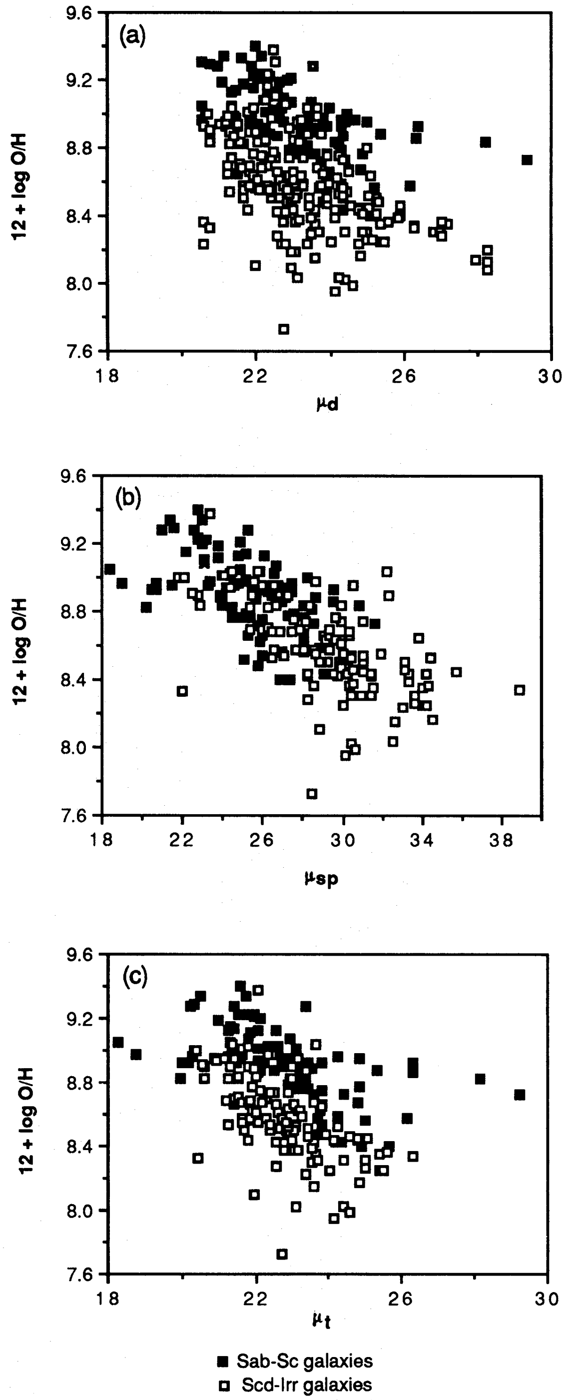

Figure 6. Correlation between oxygen abundance and surface brightness of the disc, the spheroid and total for the galaxies in the sample. The best correlation seems to be with the spheroid surface brightness. Different data points indicate early- (Sab–Sc) and late-type (Scd–Irr) galaxies given by filled and open squares respectively.

the presence of dust (and hence heavy elements), and the presence of CO (indicating H_2) is also obviously dependent on heavy elements. Thus a positive correlation of CO strength with O/H might be expected. Young & Knezek (1989) claim a marked correlation between the global ratio of molecular to atomic hydrogen with Hubble type, although they base their analysis on a single CO-strength conversion factor. We have shown in Section 3.1, Figs 4(a) and 5(a), that the central abundance increases towards earlier types whilst the gradient slope (at least for non-barred spirals) becomes shallower. Thus the mean abundance in the gas will be higher in earlier than in later types. Perhaps it is this difference in metallicity which causes (either physically or through the CO conversion factor) the correlation of H_2/H I (or rather CO/H I) fraction with Hubble type. A proper explanation must at least wait until the dependence of the CO→H_2 conversion factor on physical conditions is better understood.

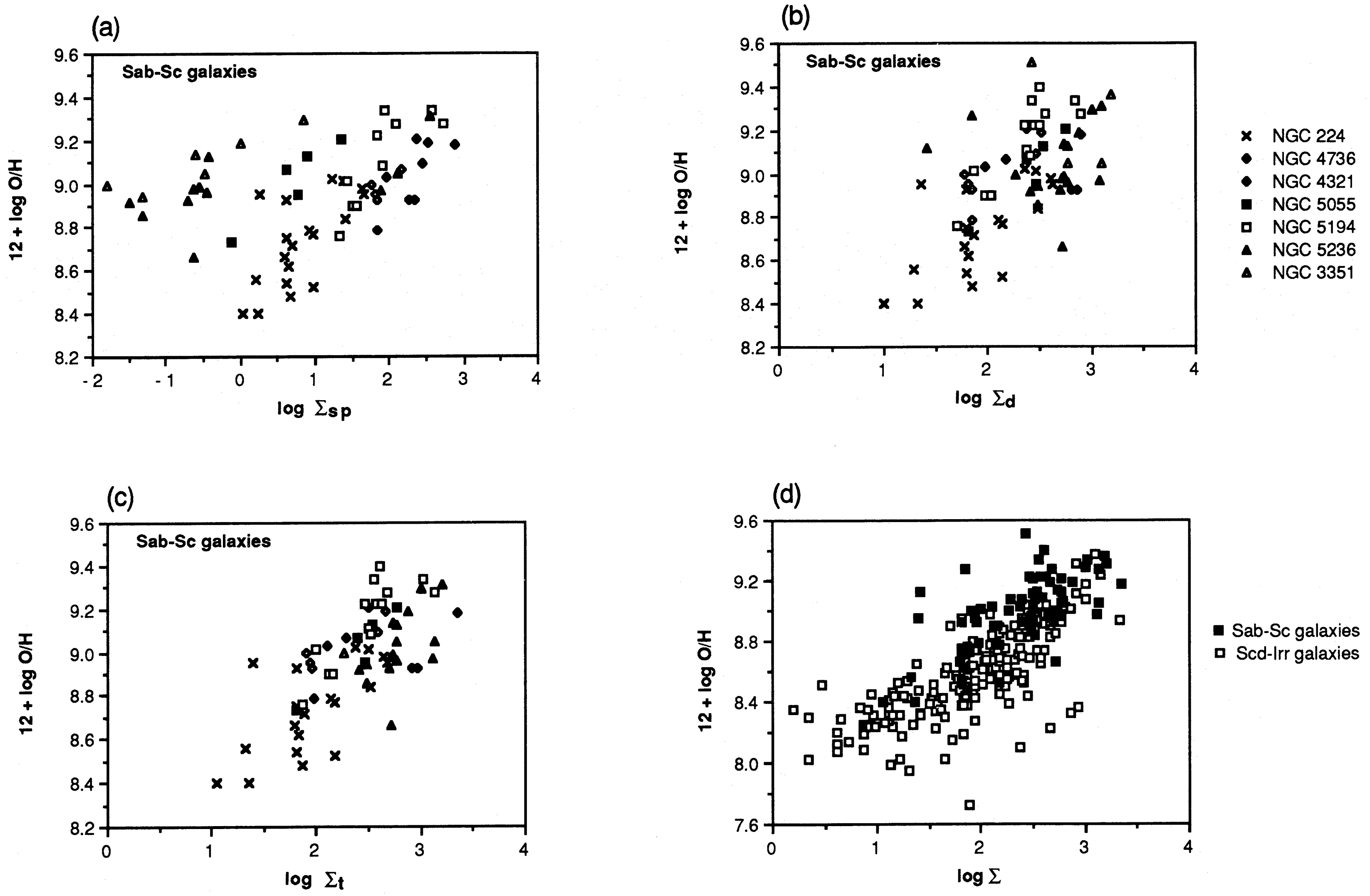

Figure 7. Correlation between the surface density and the oxygen abundance for the sample galaxies. (a)–(c) show the correlation of the surface density of the spheroid, the disc and the total (spheroid and disc) for early-type galaxies. The best fit is obtained for the total surface density. This is the surface density used in (d), where different symbols indicate early (filled squares) and late (open squares) type galaxies. For late-type galaxies only a disc component surface density is defined, and this is the one used.

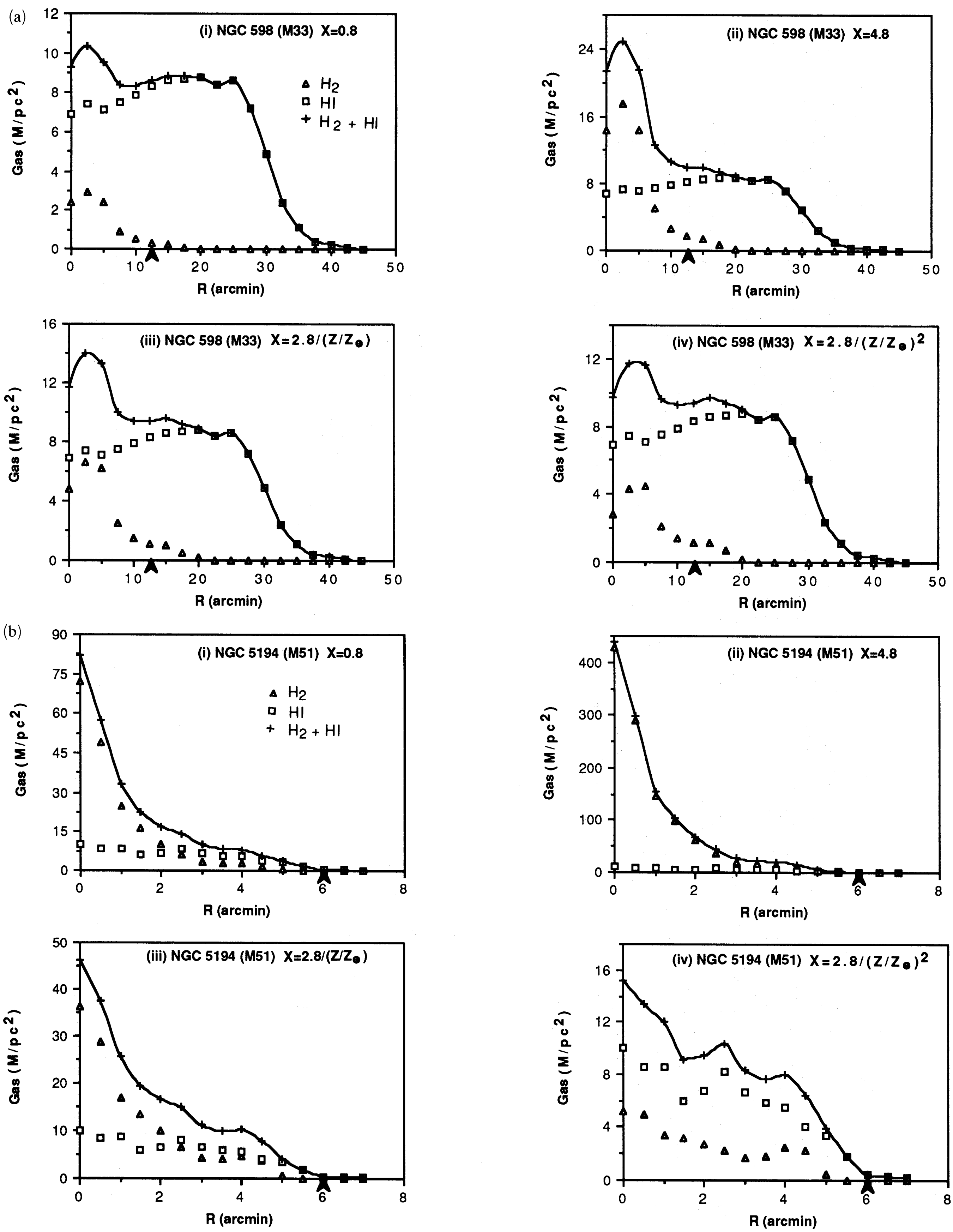

Figure 8. Examples for the galaxies (a) NGC 598 (M33) and (b) NGC 5194 (M51) of the gas distribution. The figure includes the H I (open squares), H_2 (open triangles) and total (H I + H_2) (crosses) distributions. Various values of the conversion factor have been used to obtain H_2 from the CO distribution. These are: (i) 0.8; (ii) 4.8; (iii) $2.8/(Z/Z_\odot)$; (iv) $2.8/(Z/Z_\odot)^2$. The value for $Z_\odot = 0.013$ has been used. The radius from which $Z < Z_\odot$ for each galaxy is indicated. The conversion factor using $Z_\odot$ could have been applied only to that part of the galaxy where $Z < Z_\odot$, but the plots would not have been greatly changed (see text).

Table 5. Morphology of total gas distribution as a function of CO to H_2 gas conversion factor.

Galaxy name	X = 0.8	X = 2.8	X = 4.8	Z<Z⊙	Correction	2.8/(Z/Z⊙)	2.8/(Z/Z⊙)^2
NGC 224 (M31)	peaked hat	exponential	exponential *	65' (0.84)	no	peaked hat	peaked + dip
NGC 253	peaked	steep exponential	exponential *	8' (0.82)	no	peaked (cf. 2.8)	peaked
NGC 598 (M33)	peaked hat	peaked hat	peaked hat + exponential *	12.5' (0.43)	yes	peaked hat (cf. 4.8)	peaked hat (cf. 0.8)
NGC 2403	exponential, round in centre	exponential *	exponential	2.5' (0.29)	yes	exponential (cf. 2.8)	exponential (cf. 0.8)
NGC 3031 (M81)	peaked	peaked	peaked + exponential *	7.5' (0.63)	yes CO stops at R=8'	peaked (cf. 2.8)	peaked
NGC 5194 (M51)	exponential *	exponential	exponential	6.0' (1.14)	no	exponential not so steep	flatter exponential
NGC 5236 (M83)	exponential *	exponential	exponential	10.0' (1.70)	no	exponential (cf. 0.8)	hat + exponential
NGC 5457 (M101)	peaked	exponential flat in centre	exponential *	6.0' (0.43)	yes	peaked (cf. 0.8)	peaked
NGC 6946	exponential *	exponential	exponential	7.5' (1.14)	no	exponential (cf. 0.8)	bumpy exponential
IC 342	peaked hat	exponential *	exponential	10.0 (0.89)	no	peaked hat	peaked

Columns are as follows. (1) Galaxy name. (2) Result when $X=0.8$ is used. Those galaxies with a total exponential profile are indicated. (3) As column (2) but for $X=2.8$. (4) As column (2) but for $X=4.8$. (5) Radius at which $Z<Z_\odot$, in arcmin. The value in brackets is the normalization with respect to R_{25}. (6) Indicates those galaxies for which the correction with Z should be applied, i.e., those where $Z<Z_\odot$ for a large part of the galaxy ($R/R_{25}<0.80$). (7) As column (2) but for $X=2.8/Z/Z_\odot$). (8) As column (2) but for $X=2.8/Z/Z_\odot)^2$.
The conversion factor chosen as the 'best' for each galaxy is indicated by an asterisk. As described in the text, we look for the smoothest total exponential profile and, for those galaxies with various possible results, the one with the lowest constant conversion factor is preferred.

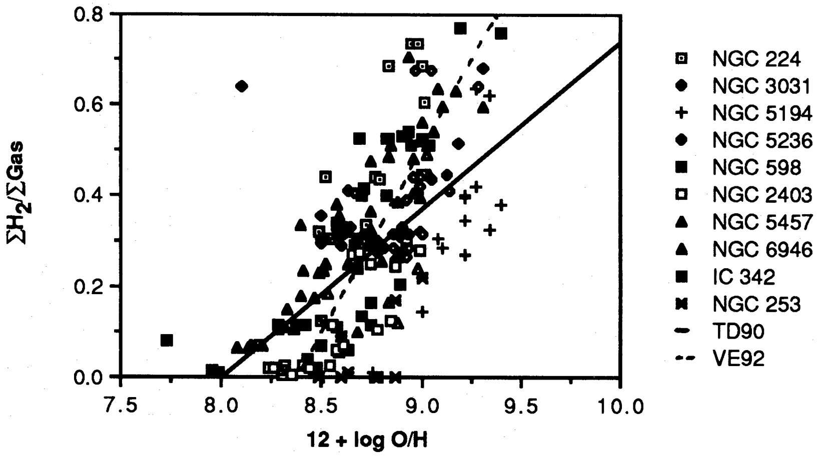

Figure 9. Relation between the molecular gas fraction ($\Sigma H_2/\Sigma$ Gas) and the oxygen abundance for the galaxies in the sample with available gas distributions. We have used the abundance of individual H II regions and our 'best' conversion factor for CO to H_2. The best fit from Tosi & Díaz (1990) is given by the solid line according to $\Sigma H_2/\Sigma \mathrm{Gas}=0.37[12+\log(\mathrm{O/H})]-2.99$. Our fit is given by the dashed line according to $\Sigma H_2/\Sigma \mathrm{Gas}=0.80[12+\log(\mathrm{O/H})]-6.68$.

3.4.2 *The calculated yields*

A useful basis for discussing chemical evolution is the simple model in which annular regions in a disc are assumed to evolve independently as closed regions without inflow or outflow (Pagel & Patchett 1975). In the instantaneous recycling approximation, the metallicity z is related to f, the gas fraction (total gas mass/total mass of stars and gas) remaining in the galaxy, by $z=p\ln(1/f)$, where p is the yield, a quantity which represents the amount of newly synthesized heavy elements returned to the interstellar medium per amount of mass locked up in long-lived stars, in each generation of star formation. The strongest, but perhaps over-optimistic, assumption is that the initial mass function and stellar physics do not vary in a way which would cause p to change. Gas flows can alter the relation between metallicity and gas fraction even with fixed formal yield p. To investigate the possibility of a varying yield, it is useful to define the effective yield, $p_{\rm eff}$, as the yield that would be deduced if a region of a galaxy were assumed to be behaving as in the simple model for chemical evolution (e.g. Edmunds 1990):

$$p_{\rm eff} = z/\ln(1/f). \quad (4)$$

We take $\log z = 1.42 + \log(\mathrm{O/H})$ and the total mass distribution from fitting the rotation curve (mainly from McCall 1982; McCall *et al.* 1985). This total mass includes disc and spheroid components for early-type galaxies, and the small spheroid contribution as if it were part of the disc component for late-type ones. Fig. 10 shows plots of z and $\ln(1/f)$ taken from the lines fitted to oxygen abundance (linear gradient) and gas fraction (for a particular conversion factor). Note that the plotted points do not represent individual H II regions, since we have used the mean relation. We have suppressed points with gas fraction $f < 0.01$, since defining a yield based on a model (even if only heuristic) with instantaneous recycling must become unrealistic at very low gas fractions.

Fig. 10 shows plots of: (i) z versus $\ln(1/f)$; (ii) $p_{\rm eff}$ versus radius (R/R_{25}), and (iii) $p_{\rm eff}$ versus z. The values adopted for the conversion factor CO to H_2, in units of 10^{20} molecule $\mathrm{cm^{-2}\,K^{-1}\,km^{-1}\,s}$, are: (a) 0.8; (b) 4.8, and (c) $2.8/(Z/Z_\odot)^2$ respectively. The general morphology of a plot for conversion factor $X = 2.8/(Z/Z_\odot)$ looks very similar to Fig. 10(a) with low constant conversion factor. If a conversion factor depending on Z is used, but set at a constant value above $Z = Z_\odot$, the appearance of plots of the form of Fig. 10 is not significantly altered.

The general appearance of these plots suggests that a low constant conversion factor (Fig. 10a) gives the smoothest relation of $p_{\rm eff}$ with z. There is not, however, a great deal of difference between the plots. If the 'best' conversion factor – i.e. that giving the smoothest gas distribution – is chosen individually for each galaxy, the resulting plots are shown in Fig. 10(d). The effective yield above $z = 0.015$ then seems remarkably universal and linearly increasing with z. It is difficult to judge how firm a result this is, since it could be partly due to the forcing of the gas distribution into an exponential. Nevertheless, the overall impression gained is that the effective yield does not vary by more than a factor of about three (0.004–0.012), increasing towards the centre, although the extent of this increase is rather dependent on the adopted conversion factor.

The general trend is for the yield to decrease as the abundance decreases. The yields decrease with radius for most galaxies apart from NGC 598 (M33) and NGC 2403. The present results for the galaxy NGC 3031 (M81) can be compared with those obtained by Garnett & Shields (1987). They did not have any H_2 data and found a constant yield with radius, but including the H_2 causes the yield to decrease with radius.

A turn in the curve of z against $\ln(1/f)$ is seen at low z in half of the galaxies. This could be due, at least in some cases, either to inaccurate extrapolation of z values where no H II regions are observed at large radii, or to the increasing dominance of dark matter at large radii, causing an overestimate of the gas-plus-star mass and artificially reducing the gas fraction.

3.5 Effect of total mass and total luminosity

Looking for global correlations, the values given by Tully (1988) for the absolute magnitude $(M_{\rm b})$, total luminosity $(L_{\rm b})$, total mass $(M_{\rm t})$, H I mass $(M_{\rm H\,I})$ and corrected H I width $(W_{\rm d})$ have been adopted after being corrected to the distances assumed for the galaxies in the present study. Using the fits to the abundance gradients given in Table 4, only $M_{\rm b}$ and $M_{\rm t}$ for non-barred galaxies are correlated with the slope. However, $M_{\rm b}$, $L_{\rm b}$, $M_{\rm t}$ and $W_{\rm d}$ seem to correlate with the intersect, i.e. the abundance extrapolated to the centre of a galaxy. Fig. 11 shows some of these correlations with the intersect and with morphological type as given by T. The correlation of T with the slope and the intersect was shown in Section 3.1 (Figs 4 and 5). The total mass defined by Tully is biased in the sense that it does not take into account a dark matter component. In Section 3.6 we correct for this by using the outer gradient of the rotation curve, which is an indicator of the amount of dark matter (Persic & Salucci 1990), and find a correlation between this outer velocity gradient and the central intersect abundance but no correlation with the abundance gradient.

We find no obvious correlation between slope or intersect with $(U-B)$ or $(B-V)$ colours taken from RC2 (de Vaucouleurs *et al.* 1976), although (as expected) the colours correlate roughly with morphological type. The colour is dominated by star formation effects in spirals, so we would not necessarily expect a direct relation between colour and abundance, and the lack of correlation indicates that there is no clear relation between current star formation rates and abundances or gradients.

As a reference, Table 3 gives the absolute magnitudes $(M_{\rm b})$ and $(B-V)$ colours adopted for the galaxies in the present sample.

3.6 The arm class and the outer gradient of the rotation curve

A correlation has been found (Biviano *et al.* 1991; Elmegreen & Elmegreen 1991, unpublished) between the arm class as defined by Elmegreen & Elmegreen (1982) and the outer gradient of the rotation curve which is defined in two ways (Log Vel Grad and Out Vel Grad), following Whitmore (1984), Persic & Salucci (1986) and Biviano *et al.* (1991). Persic & Salucci (1990) propose that there is a simple linear correspondence between the fractional amount of dark matter at the disc edge and the outer rotation curve gradient.

For the sample of galaxies in this paper, we find a clear correlation of only the central intersect with the outer gradient of the rotation curve (i.e. the mass fraction of dark matter), but we find no correlation of the intersect with arm class. No correlations with the abundance gradient are found. Fig. 12 shows examples of some of these correlations. Those in Fig. 12(b) and (c) agree with those found by Whitmore (1984). A correlation between the gradient of the rotation curve and the absolute magnitude (Rubin *et al.* 1985; Persic

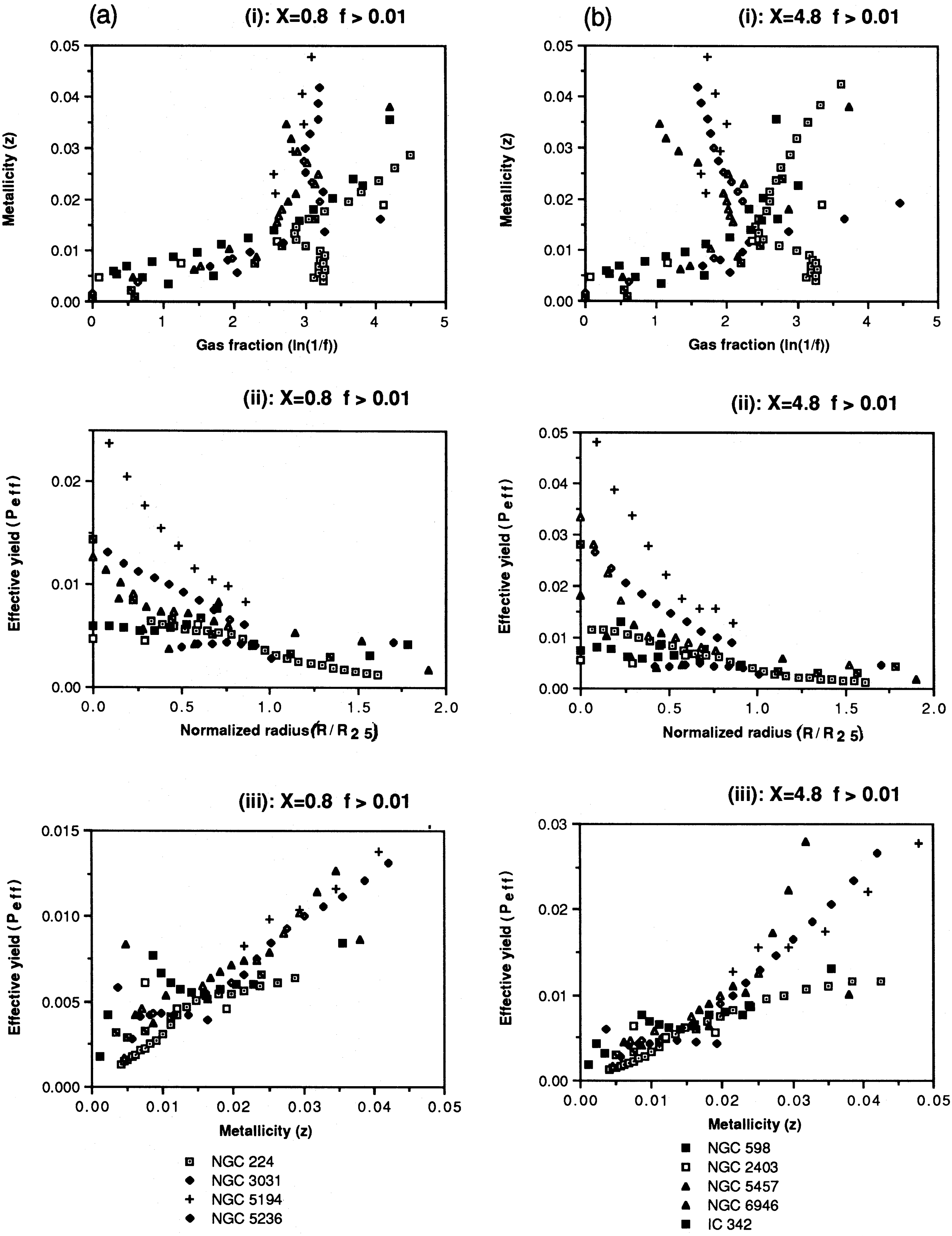

Figure 10. Distribution for the galaxies in the present sample of: (i) z versus $\ln(1/f)$; (ii) effective yield $p_{\rm eff}$ versus R/R_{25}, and (iii) $p_{\rm eff}$ versus z, using as conversion factor X for CO to H_2: (a) 0.8; (b) 4.8; (c) $2.8/(Z/Z_\odot)^2$, and (d) 'best' as described in the text. Those points where the gas fraction was less than 1 per cent, i.e. $\ln(1/f) > 4.5$, have been suppressed.

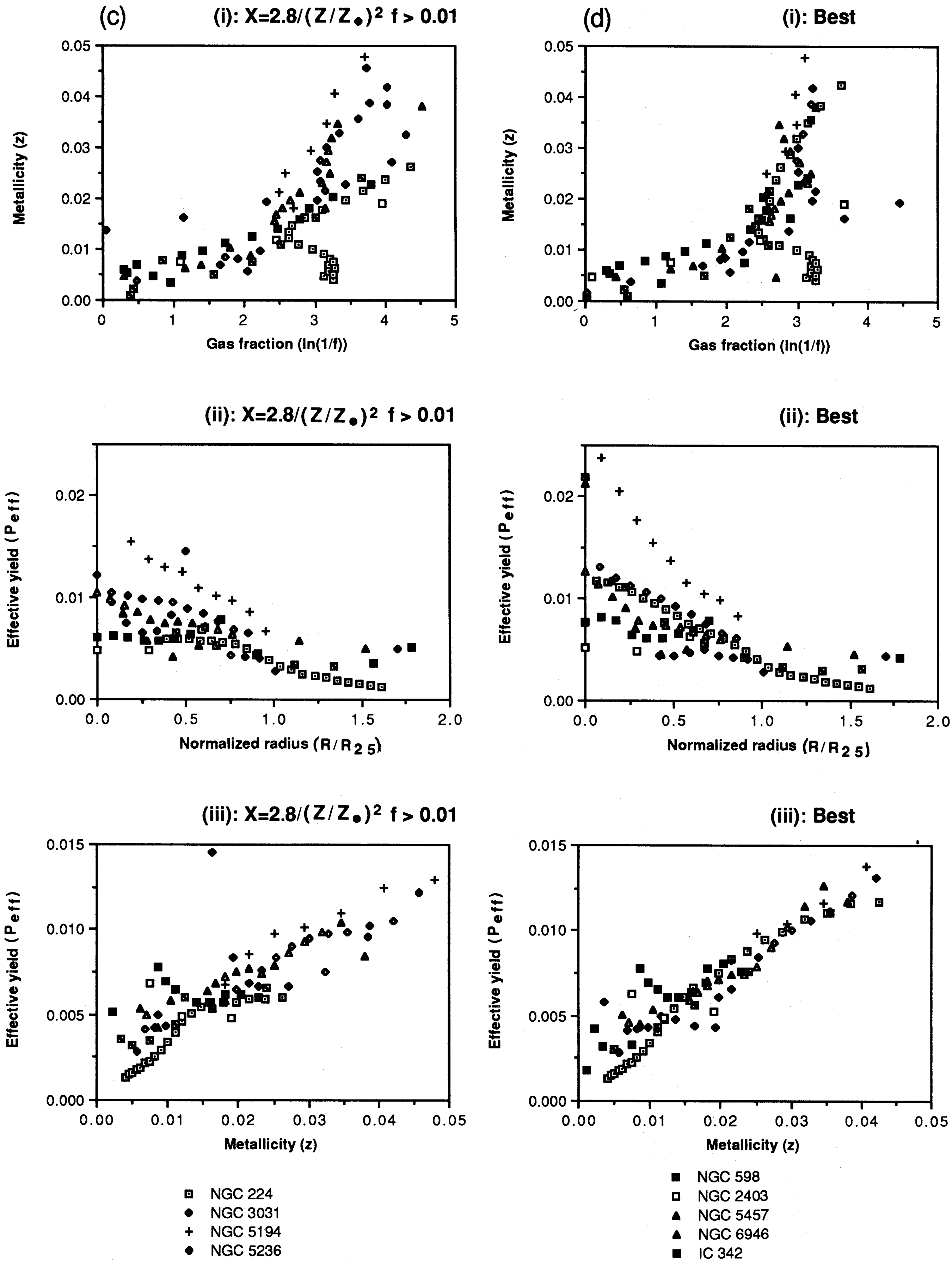

Figure 10 – *continued*

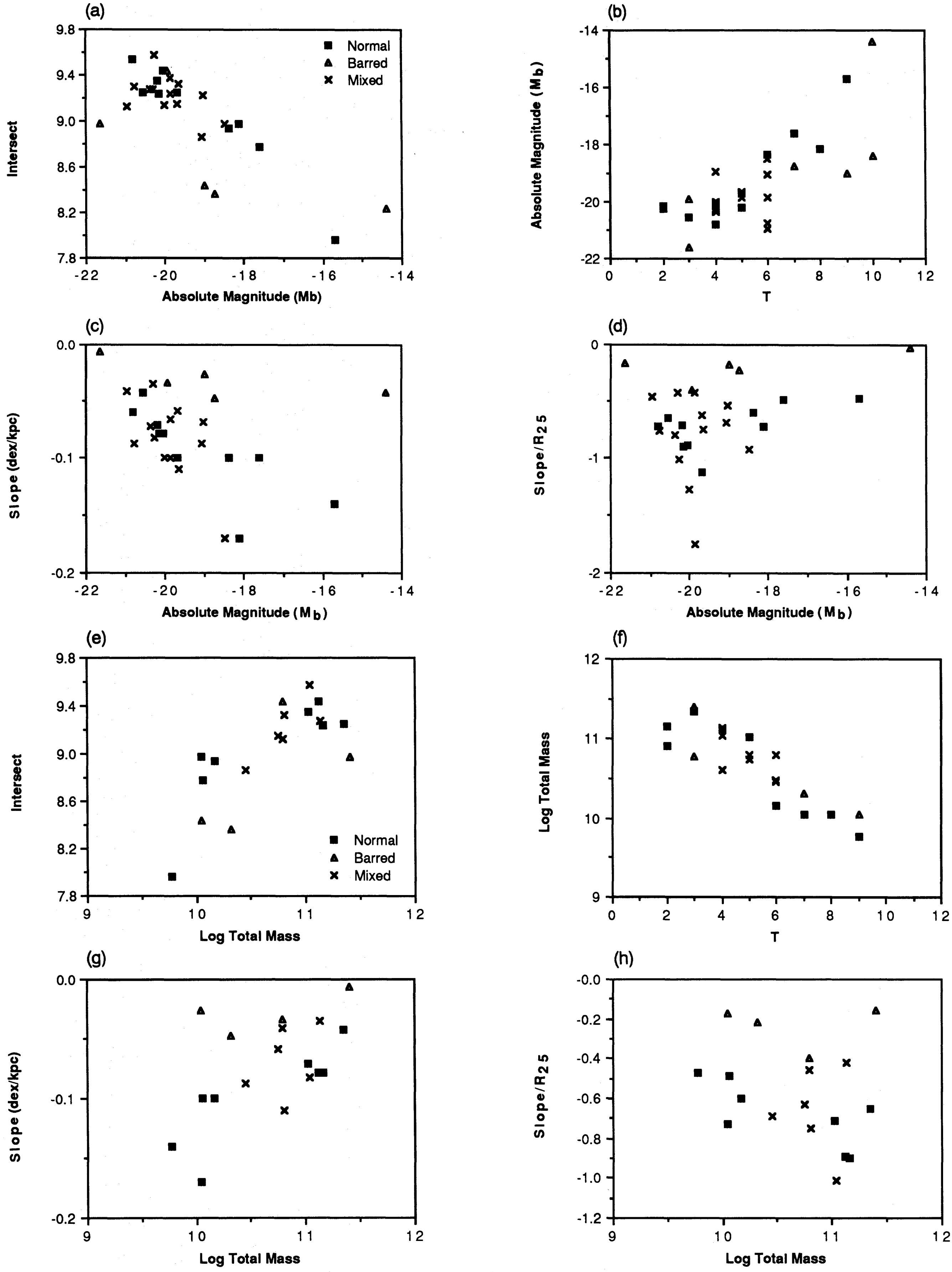

Figure 11. Examples of the correlations found between the intersect and the slope, defined by fitting the oxygen gradient, with the absolute magnitude (M_b) and the total mass for the galaxies in the sample. The correlations of these with morphological type (T) are also shown. Different symbols indicate, as previously, non-barred (filled squares), barred (open triangles) and mixed (crosses) galaxies.

& Salucci 1991) exists too (even if it is not found with the present sample), so both measures of mass – absolute magnitude and dark matter – correlate with the central abundance. We do find a correlation between the arm class and the absolute magnitude, in agreement with Elmegreen & Elmegreen (1982, 1987).

4 DISCUSSION AND CONCLUSIONS

The correlations of global properties of spiral galaxies with their abundance gradients are summarized in Table 6. The most apparent trends are that the central abundances are related (both for barred and non-barred galaxies) to the total mass or brightness of the galaxy, which in this sample increases on average towards earlier Hubble type. The gradients in barred galaxies are significantly shallower than for non-barred galaxies, and in the latter case they are steeper (in dex kpc^{-1}) in later Hubble types.

The abundance at any point in a spiral disc appears well correlated with the local surface mass density. The correlation with local surface brightness is not as good and it appears that the spheroid surface brightness may be more significant than the total surface brightness – although the uncertainty in disc/spheroid separation should not be forgotten.

The calculation of gas fractions and hence chemical yields for these galaxies *must be regarded as very provisional* because of uncertainties in the molecular gas conversion factors. Our initial results suggest an effective yield that decreases with radius and/or increases with abundance, although never varying greatly from the range 0.004–0.012. Figs 13(a)–(d) compare the correlations of metallicity versus gas fraction and versus the effective yield, using individual H II regions and using the fitted lines to the abundance gradients. Both diagrams are similar, but the individual H II regions show a larger scatter. Peimbert & Serrano (1982) suggested a metallicity-dependent true yield, $p = 0.002 + 0.6\,z$, which corresponds to an effective yield

$$p_{\rm eff} = 0.6\,z/\ln(1+300\,z). \quad (5a)$$

Their formula is plotted with the empirical data for individual H II regions in Fig. 13(e). If interpreted on a locally closed simple model, a true yield of the form $p = 0.003\,[1+(z/0.009)^2]^{3/2}$, which corresponds to an effective yield

$$p_{\rm eff} = 0.003\,[1+(z/0.009)^2]^{1/2}, \quad (5b)$$

gives a better fit to the observations (see Fig. 13e). A straight line of the form

$$p_{\rm eff} = 0.0016 + 0.29\,z, \quad (5c)$$

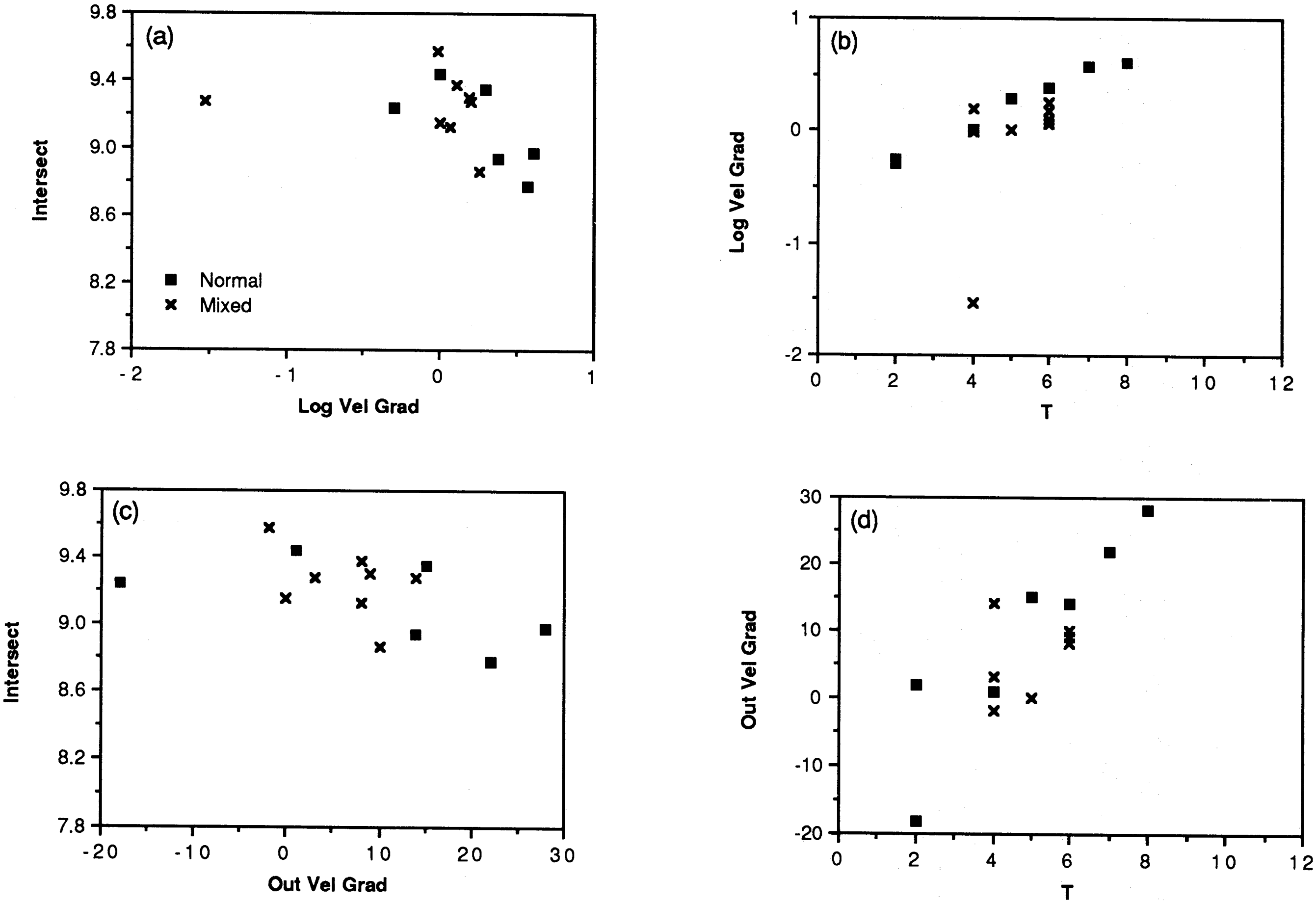

Figure 12. Correlations found between the intersect as defined from the fitting to oxygen abundances and the outer gradient of the rotation curve defined as either Log Vel Grad or Out Vel Grad (Biviano *et al.* 1991). Again the correlations of these with morphological type (T) are also shown. Different symbols indicate non-barred (filled squares), and mixed (crosses) galaxies. Log Vel Grad is directly proportional to $M_{\rm disc}/M_{\rm total}$ (Persic & Salucci 1990).

	Intersect (Abundance Gradient)	Slope (dex/kpc) (Abundance Gradient)	Slope/R25 (Abundance Gradient)	T	Mb	Log Total Mass	Log HI Mass	Mh/Lb	Mh/Mt	Mt/Lb	Arm Class	Log Vel Grad *	Out Vel Grad *
Intersect (Abundance Gradient)		-	-	C	C	C	-	C :	C	-	-	NB :	-
Slope (dex/kpc) (Abundance Gradient)			-	NB	NB	NB :	-	-	-	-	- (1).	-	-
Slope/R25 (Abundance Gradient)				-	-	-	-	-	NB :	-	-	-	-
T					C :	C	-	C :	C :	-	-	NB :	NB
Mb						C	C	C ::	-	-	C :	-	-
Log Total Mass							C :	C ::	C ::	-	C ::	NB :	NB ::
Log HI Mass								-	-	-	-	-	-
Mh/Lb									C	-	-	-	-
Mh/Mt										-	-	NB ::	NB ::
Mt/Lb											C ::	-	-
Arm class												-	-
Log Vel Grad *													NB
Out Vel Grad *													

COMMENTS:

C Correlation for all types
NB Correlation for non-barred only
: Weak correlation only
:: Very weak correlation

(1). Arm class less than 2 have steep gradient.
* No data available for barred spirals.

Gradients of non barred spirals are greater than those of barred ones, both in dex/kpc and dex/R25.
The HI width is not included because it is used to derive the total mass and so there is a very good correlation between them.

Table 6. Summary of the various correlations found between the global properties of the galaxies in the sample. These include: the fitted oxygen abundance gradient, characterized by the central intersect and the slope in dex kpc^{-1} or normalized to R_{25}; the morphological type (T); the absolute blue magnitude (M_b); the total mass (log M_t); the H I mass (log M_{HI}); the H I mass over absolute blue luminosity (M_{HI}/L_b); the H I over total mass (M_{HI}/M_t); the total mass over absolute blue luminosity (M_t/L_b); the arm class and the external gradient of the velocity rotation curve of the galaxy, characterized in two ways (Log Vel Grad and Out Vel Grad; Biviano *et al.* 1991). Log Vel Grad is directly proportional to the dark matter mass fraction in a galaxy (Persic & Salucci 1990).

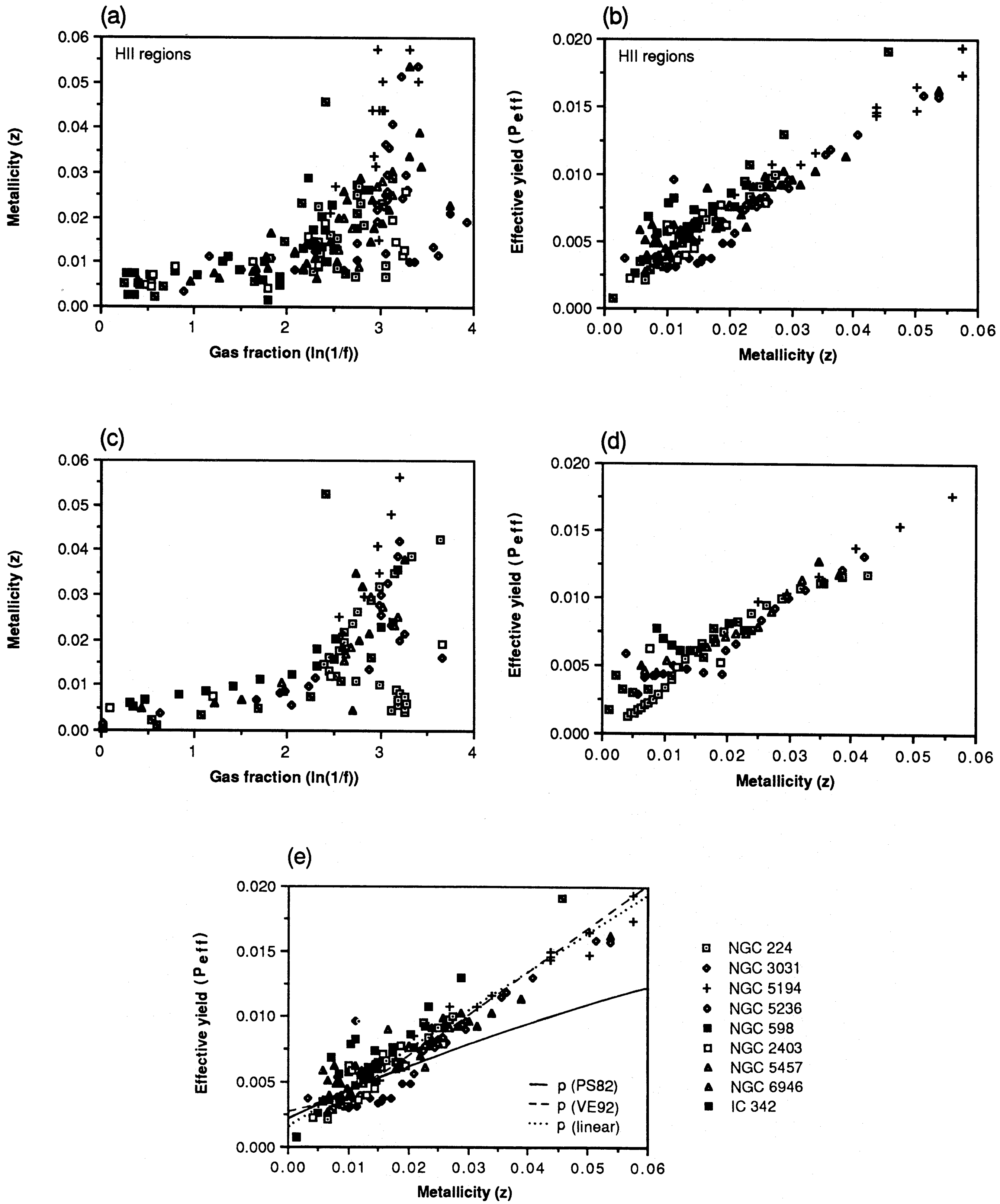

Figure 13. Panels (a) and (b) show correlations between metallicity (z) and gas fraction [$\ln(1/f)$], and effective yield ($p_{\rm eff}$) and metallicity (z) for individual H II regions in the 'best' galaxies (Fig. 10d). Panels (c) and (d) show the same, using the fitted lines to the oxygen abundance gradients. Panel (e) presents various model fits to the yield versus metallicity plot for individual H II regions. The full line is given by $p_{\rm eff}=0.6\,z/\ln(1+300\,z)$ from a true yield $p=0.002+0.6\,z$ (Peimbert & Serrano 1982). The dashed line is given by $p_{\rm eff}=0.003[1+(z/0.009)^2]^{1/2}$, from a true yield $p=0.003[1+(z/0.009)^2]^{3/2}$, as suggested in the present study. An effective yield of the form $p_{\rm eff}=0.0016+0.29\,z$, which corresponds to a true yield of the form $p=53\,z^2+0.58\,z+0.0016$, is also indicated (dotted line). Note that a simple model with constant yield would give a horizontal line.

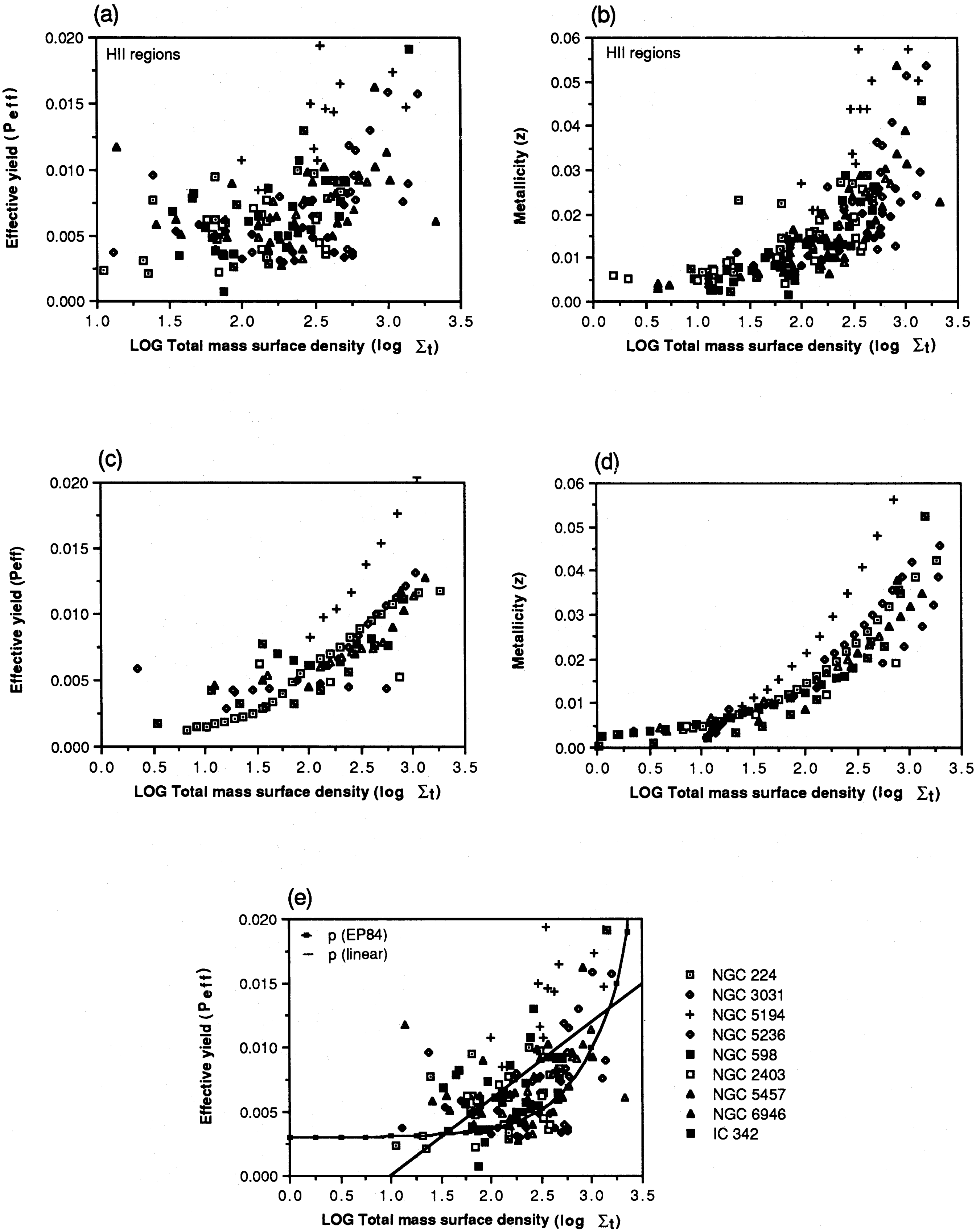

Figure 14. Panels (a) and (b) show the correlations with surface density ($\log \Sigma_t$) of the effective yield (p_{eff}) and the metallicity (z) for the individual H II regions in the 'best' sample galaxies (Fig. 10d). Panels (c) and (d) show the same using the fitted lines to the oxygen abundance gradients. Panel (e) presents various model fits to the yield versus surface density plot for individual H II regions. They include $p_{eff} = 0.003 + 7 \times 10^{-6}\ \Sigma_t$, as suggested by Edmunds & Pagel (1984a), and a straight-line fit of the form $p_{eff} = 0.006\ (\log \Sigma_t - 1)$.

which corresponds to a true yield $p = 53\,z^2 + 0.58\,z + 0.0016$, also gives a good fit to the data. However, this effective yield at low metallicities is probably too low compared with the values obtained for irregular galaxies (0.004–0.006) (Lequeux *et al.* 1979; Serrano & Peimbert 1981; Vigroux, Stasinska & Comte 1987). We note that a yield increasing with metallicity is in the opposite sense to that implied by Maeder's (1992) study based on theoretical models of massive star evolution with metallicity-dependent mass loss.

It is not easy to decide with which property the yield is varying. Possible candidates are the surface density, the radius or the metallicity. The good correlation between yield and metallicity is shown in Figs 13(b) and (d). In Fig. 14 we compare the correlations of yield and metallicity with surface density, for individual H II regions and for the fitted abundance gradients. Again the scatter is larger in the first case, but the correlation of metallicity with surface density is much tighter than that observed for the yield. We have fitted the function suggested by Edmunds & Pagel (1984):

$$p_{\rm eff} = 0.003 + 7 \times 10^{-6}\,\Sigma_{\rm t}, \qquad (6a)$$

and a straight line of the form

$$p_{\rm eff} = 0.006\,(\log \Sigma_{\rm t} - 1) \qquad (6b)$$

in Fig. 14(e). So far, it seems that the yield varies more as a function of metallicity or radius than as a function of surface density.

The origin of the correlations we have found will be discussed elsewhere, but they must hold valuable clues for understanding the formation and evolution of spiral galaxies. Extension of the data set to a wider sample, particularly to disc galaxies of more extreme properties – for example, large, low surface brightness discs like Malin 1 (Impey & Bothun 1989) and systems with high surface density (e.g. Rubin, Ford & Thonnard 1980, 1985) – would obviously be desirable.

ACKNOWLEDGMENTS

We are particularly indebted to the valuable compilations of data published by Marshall McCall. MBV is grateful for the financial support of a SERC fellowship. We thank R. B. C. Henry and S. Josey for helpful comments on an early version of the manuscript, and B. E. J. Pagel for encouragement. We also thank the anonymous referee for useful comments.

REFERENCES

Biviano, A., Girardi, M., Giuricin, G., Mardirossian, F. & Mezzetti, M., 1991. *Astrophys. J.*, **376**, 458.
Boroson, T., 1981. *Astrophys. J. Suppl.*, **46**, 177.
Cepa, J. & Beckman, J. E., 1990. *Astrophys. J.*, **349**, 497.
Clarke, C. J., 1989. *Mon. Not. R. astr. Soc.*, **238**, 283.
de Vaucouleurs, G. & Pence, W. D., 1978. *Astr. J.*, **83**, 1163.
de Vaucouleurs, G., de Vaucouleurs, A. & Corwin, H. G., Jr, 1976. *Second Reference Catalogue of Bright Galaxies*, Texas University Press, Austin (RC2).
Díaz, A. I., 1989. In: *Evolutionary Phenomena in Galaxies*, p. 377, eds Beckman, J. E. & Pagel, B. E. J., Cambridge University Press, Cambridge.
Díaz, A. I. & Tosi, M., 1984. *Mon. Not. R. astr. Soc.*, **208**, 365.
Edmunds, M. G., 1989. In: *Evolutionary Phenomena in Galaxies*, p. 356, eds Beckman, J. E. & Pagel, B. E. J., Cambridge University Press, Cambridge.
Edmunds, M. G., 1990. *Mon. Not. R. astr. Soc.*, **246**, 678.
Edmunds, M. G. & Pagel, B. E. J., 1982. *Mon. Not. R. astr. Soc.*, **198**, 1089.
Edmunds, M. G. & Pagel, B. E. J., 1984a. *Mon. Not. R. astr. Soc.*, **211**, 507.
Edmunds, M. G. & Pagel, B. E. J., 1984b. In: *Stellar Nucleosynthesis*, p. 341, eds Chiosi, C. & Renzini, A., Reidel, Dordrecht.
Edmunds, M. G. & Phillipps, S., 1989. *Mon. Not. R. astr. Soc.*, **241**, 9P.
Edmunds, M. G. & Greenhow, R., 1992. *Mon. Not. R. astr. Soc.*, to be submitted.
Elmegreen, D. M. & Elmegreen, B. G., 1982. *Mon. Not. R. astr. Soc.*, **201**, 1021.
Elmegreen, D. M. & Elmegreen, B. G., 1987. *Mon. Not. R. astr. Soc.*, **314**, 3.
Evans, I. N., 1986. *Astrophys. J.*, **309**, 544.
Freeman, K. C., 1970. *Astrophys. J.*, **160**, 811.
Garnett, D. R. & Shields, G. A., 1987. *Astrophys. J.*, **317**, 82.
Güsten, R. & Mezger, P. G., 1982. *Vistas Astr.*, **26**, 159.
Impey, C. & Bothun, G., 1989. *Astrophys. J.*, **341**, 89.
Kent, S. M., 1985. *Astrophys. J. Suppl.*, **59**, 115.
Kent, S. M., 1986. *Astr. J.*, **91**, 1301.
Kormendy, J., 1977. *Astrophys. J.*, **217**, 406.
Lacey, C. G. & Fall, S. M., 1985. *Astrophys. J.*, **290**, 154.
Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A. & Torres-Peimbert, S., 1979. *Astr. Astrophys.*, **80**, 155.
Maeder, A., 1992. *Astr. Astrophys.*, in press.
Maloney, P., 1990. In: *The Interstellar Medium in Galaxies*, p. 493, eds Thronson, H. A., Jr & Shull, J. M., Kluwer, Dordrecht.
Maloney. P. & Black, J. H., 1988. *Astrophys. J.*, **325**, 389.
Mayor, M. & Vigroux, L., 1981. *Astr. Astrophys.*, **98**, 1.
McCall, M. L., 1982. *PhD thesis*, University of Texas, Austin.
McCall, M. L., 1984. *Mon. Not. R. astr. Soc.*, **208**, 253.
McCall, M. L., Rybski, P. M. & Shields, G. A., 1985. *Astrophys. J. Suppl.*, **57**, 1.
Mendoza, C., 1983. In: *Planetary Nebulae, IAU Symp No. 103*, p. 143, ed. Flower, D. R., Reidel, Dordrecht.
Pagel, B. E. J., 1989. *Rev. Mex. Astr. Astrofis.*, **18**, 161.
Pagel, B. E. J. & Patchett, B. E., 1975. *Mon. Not. R. astr. Soc.*, **172**, 13.
Pagel, B. E. J. & Edmunds, M. G., 1981. *Ann. Rev. Astr. Astrophys.*, **19**, 77.
Pagel, B. E. J., Edmunds, M. G., Blackwell, D. A., Chun, M. S. & Smith, G., 1979. *Mon. Not. R. astr. Soc.*, **189**, 95.
Peimbert, M. & Serrano, A., 1982. *Mon. Not. R. astr. Soc.*, **198**, 563.
Persic, M. & Salucci, P., 1986. *Mon. Not. R. astr. Soc.*, **223**, 303.
Persic, M. & Salucci, P., 1990. *Mon. Not. R. astr. Soc.*, **245**, 577.
Persic, M. & Salucci, P., 1991. *Astrophys. J.*, **368**, 60.
Phillipps, S. & Edmunds, M. G., 1991. *Mon. Not. R. astr. Soc.*, **251**, 84.
Phillipps, S., Edmunds, M. G. & Davies, J., 1990. *Mon. Not. R. astr. soc.*, **244**, 168.
Phillips, M. M., Pagel, B. E. J., Edmunds, M. G. & Díaz, A. I., 1984. *Mon. Not. R. astr. Soc.*, **210**, 701.
Pitts, E. & Tayler, R. J., 1989. *Mon. Not. R. astr. Soc.*, **240**, 373.
Rots, A. H., 1975. *Astr. Astrophys.*, **45**, 43.
Rubin, V. C., Ford, W. K. & Thonnard, N., 1980. *Astrophys. J.*, **238**, 471.
Rubin, V. C., Ford, W. K. & Thonnard, N., 1982. *Astrophys. J.*, **261**, 439.
Rubin, V. C., Burstein, D., Ford, W. K. & Thonnard, N., 1985. *Astrophys. J.*, **289**, 81.
Serrano, A. & Peimbert, M., 1981. *Rev. Mex. Astr. Astrofis.*, **5**, 109.
Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C. & Pottasch, S. R., 1983. *Mon. Not. R. astr. Soc.*, **204**, 53.
Shields, G. A., 1990. *Ann. Rev. Astr. Astrophys.*, **28**, 525.
Shields, G. A., Skillman, E. D. & Kennicutt, R. C., Jr, 1991. *Astrophys. J.*, **371**, 82.
Simien, F. & de Vaucouleurs, G., 1986. *Astrophys. J.*, **302**, 564.
Skillman, E. D., 1989. *Astrophys. J.*, **347**, 883.
Sommer-Larsen, J. & Yoshii, Y., 1989. *Mon. Not. R. astr. Soc.*, **238**, 133.

Tosi, M. & Díaz, A. I., 1990. *Mon. Not. R. astr. Soc.,* **246,** 616.
Tully, R. B., 1988. *Nearby Galaxy Catalogue,* Cambridge University Press, Cambridge.
van der Kruit, P. C., 1987. *Astr. Astrophys.,* **173,** 49.
Vigroux, L., Stasinska, G. & Comte, G., 1987. *Astr. Astrophys.,* **172,** 15.
Vilchez, J. M., Pagel, B. E. J., Díaz, A. I., Terlevich, E. & Edmunds, M. G., 1988. *Mon. Not. R. astr. Soc.,* **235,** 633.
Wang, Z., 1990. *Astrophys. J.,* **360,** 543.
Whitmore, B. C., 1984. *Astrophys. J.,* **278,** 61.
Young, J. S., 1990. In: *The Interstellar Medium in Galaxies,* p. 67, eds Thronson, H. A., Jr & Shull, J. M., Kluwer, Dordrecht.
Young, J. S. & Knezek, P. M., 1989. *Astrophys. J. Lett.,* **347,** L55.

APPENDIX A: REFERENCES FOR TABLE 1

Chemical data references

1 Webster, B. L. & Smith, M. G., 1983. *Mon. Not. R. astr. Soc.,* **204,** 743.
2 Blair, W. P., Kirshner, R. P. & Chevalier, R. A., 1981. *Astrophys. J.,* **247,** 879.
3 Blair, W. P., Kirshner, R. P. & Chevalier, R. A., 1982. *Astrophys. J.,* **254,** 50.
4 Dennefeld, M. & Kunth, D., 1981. *Astr. J.,* **86,** 989.
5 Pagel, B. E. J., Edmunds, M. G., Blackwell, D. E., Chun, M. S. & Smith, G., 1979. *Mon. Not. R. astr. Soc.,* **189,** 95.
6 Edmunds, M. G. & Pagel, B. E. J., 1984. *Mon. Not. R. astr. Soc.,* **211,** 507.
7 Deharveng, L., Caplan, J., Lequeux, J., Azzopardi, M., Breysacher, J., Tarenghi, M. & Westerlund, B., 1988. *Astr. Astrophys. Suppl.,* **73,** 407.
8 D'Odorico, S., Rosa, M. & Wampler, E. J., 1983. *Astr. Astrophys. Suppl.,* **53,** 97.
9 Kwitter, K. B. & Aller, L. H., 1981. *Mon. Not. R. astr. Soc.,* **195,** 939.
10 McCall, M. L., 1982. *PhD thesis,* University of Texas, Austin. McCall, M. L., Rybski, P. M. & Shields, G. A., 1985. *Astrophys. J. Suppl.,* **57,** 1.
11 Searle, L., 1971. *Astrophys. J.,* **168,** 327.
12 Smith, H. D., 1975. *Astrophys. J.,* **199,** 591.
13 Vilchez, J. M., Pagel, B. E. J., Díaz, A. I., Terlevich, E. & Edmunds, M. G., 1988. *Mon. Not. R. astr. Soc.,* **235,** 633.
14 Díaz, A. I., Terlevich, E., Pagel, B. E. J., Vilchez, J. M. & Edmunds, M. G., 1987. *Mon. Not. R. astr. Soc.,* **226,** 19.
15 Pagel, B. E. J., Edmunds, M. G. & Smith, G., 1980. *Mon. Not. R. astr. Soc.,* **193,** 219.
16 Alloin, D., Edmunds, M. G., Lindblad, P. O. & Pagel, B. E. J., 1981. *Astr. Astrophys.,* **101,** 377.
17 Garnett, D. R. & Shields, G. A., 1987. *Astrophys. J.,* **317,** 82.
18 McCall, M. L., Shields, G. A. & Rybski, P. M., 1981. *Publs astr. Soc. Pacif.,* **93,** 273.
19 Vilchez, J. M., Edmunds, M. G. & Pagel, B. E. J., 1988. *Publs astr. Soc. Pacif.,* **100,** 1428.
20 Brand, P. W. J. L., Coulson, I. M. & Zealey, W. J., 1981. *Mon. Not. R. astr. Soc.,* **195,** 353.
21 Dufour, R. J., Talbot, R. J., Jr, Jensen, E. B. & Shields, G. A., 1980. *Astrophys. J.,* **236,** 119.
22 Rayo, J. F., Peimbert, M. & Torres-Peimbert, S., 1982. *Astrophys. J.,* **255,** 1.
23 Hawley, S. A. & Phillips, M. M., 1980. *Astrophys. J.,* **235,** 783.
24 Stauffer, J. R. & Bothun, G. D., 1984. *Astr. J.,* **89,** 1702.
25 Díaz, A. I., Terlevich, E., Vilchez, J. M., Pagel, B. E. J. & Edmunds, M. G., 1991. *Mon. Not. R. astr. Soc.,* **253,** 245.
26 Shields, G. A., Skillman, E. D. & Kennicutt, A. C., Jr, 1991. *Astrophys. J.,* **371,** 82.
27 Fierro, J., Torres-Peimbert, S. & Peimbert, M., 1986. *Publs astr. Soc. Pacif.,* **98,** 1032.
28 Zaritsky, D., Elston, R. & Hill, J. M., 1990. *Astr. J.,* **99,** 1108.
29 Belley, J. & Roy, J. R., 1991. *Astrophys. J. Suppl.,* **78,** 61.
30 Evans, I. N., 1986. *Astrophys. J.,* **309,** 544.

CO data references

1 Lada, C. J., Margulis, M., Sofue, Y., Nakai, N. & Handa, T., 1988. *Astrophys. J.,* **328,** 143.
2 Boulanger, F., Bystedt, J., Casoli, F. & Combes, F., 1984. *Astr. Astrophys.,* **140,** L5.
3 Ryden, B. S. & Stark, A. A., 1986. *Astrophys. J.,* **305,** 823.
4 Ichikawa, T., Nakano, M. & Tanaka, Y. D., 1987. In: *Star Forming Regions, IAU Symp. No. 115,* p. 622, eds Peimbert, M. & Jugaku, J., Reidel, Dordrecht.
5 Vogel, S. N., Boulanger, F. & Ball, R., 1987. *Astrophys. J. Lett.,* **321,** L145.
6 Encrenaz, P. J., Stark, A. A., Combes, F. & Wilson, R. W., 1979. *Astr. Astrophys.,* **78,** L1.
7 Young, J. S. & Scoville, N., 1982. *Astrophys. J. Lett.,* **260,** L11.
8 Sandqvist, A., Elfhag, T. & Jorsater, S., 1988. *Astr. Astrophys.,* **201,** 223.
9 Dettmar, R. J. & Heithausen, H., 1989. *Astrophys. J. Lett.,* **344,** L61.
10 Kenney, J. D. & Young, J. S., 1986. *Astrophys. J. Lett.,* **301,** L13.
11 Kenney, J. D. & Young, J. S., 1988. *Astrophys. J. Suppl.,* **66,** 261.
12 Elmegreen, D. M. & Elmegreen, B. G., 1982. *Astr. J.,* **87,** 626.
13 Tacconi, L. J. & Young, J. S., 1985. *Astrophys. J.,* **290,** 602.
14 Garman, L. E. & Young, J. S., 1986. *Astr. Astrophys.,* **154,** 8.
15 Johansson, L. E. B. & Booth, R. S., 1987. In: *Star Forming Regions, IAU Symp. No. 115,* p. 659, eds Peimbert, M. & Jugaku, J., Reidel, Dordrecht.
16 Rydbeck, G., Hjalmarson, Å. & Rydbeck, O. E. H., 1985. *Astr. Astrophys.,* **144,** 282.
17 Rickard, L. J. & Palmer, P., 1981. *Astr. Astrophys.,* **102,** L13.
18 Scoville, N. & Young, J. S., 1983. *Astrophys. J.,* **265,** 148.
19 Vogel, S. N., Kulkarni, S. R. & Scoville, N. Z., 1988. *Nature,* **334,** 402.
20 Combes, F., Encrenaz, P. J., Lucas, R. & Weliachew, L. 1977. *Astr. Astrophys.,* **55,** 311.
21 Rickard, L. J., Palmer, P., Morris, M., Turner, B. E. & Zuckerman, B., 1977. *Astrophys. J.,* **213,** 673.
22 Combes, F., Encrenaz, P. J., Lucas, R. & Weliachew, L., 1978. *Astr. Astrophys.,* **67,** L13.
23 Solomon, P. M., Barrett, J., Sanders, D. B. & de Zafra, R., 1983. *Astrophys. J. Lett.,* **266,** L103.
24 Blitz, L., Israel, F. P., Neugebauer, G., Gatley, I., Lee, T. J. & Beattie, D. H., 1981. *Astrophys. J.,* **249,** 76.
25 Young, J. S. & Scoville, N., 1982. *Astrophys. J.,* **258,** 467.
26 Tacconi, L. J. & Young, J. S., 1986. *Astr. J.,* **308,** 600.
27 Sofue, Y., Doi, M., Ishizuki, S., Nakai, N. & Handa, T., 1988. *Publs astr. Soc. Japan,* **40,** 511.
28 Brouillet, N., Baudry, A. & Combes, F., 1988. *Astr. Astrophys.,* **196,** L17.
29 Encrenaz, P. J., Stark, A. A., Combes, F. & Wilson, R. W., 1979. *Astr. Astrophys.,* **78,** L1.
30 Scoville, N. Z., Soifer, B. T., Neugebauer, G., Young, J. S., Matthews, K. & Yerka, J., 1985. *Astrophys. J.,* **289,** 129.
31 Lo, K. Y., Ball, R., Masson, C. R., Phillips, T. G., Scott, S. & Woody, D. P., 1987. *Astrophys. J. Lett.,* **317,** L63.
32 Rand, R. J. & Kulkarni, S. R., 1990. *Astrophys. J. Lett.,* **349,** L43.
33 Sage, L. J., & Westpfahl, D. J., 1991. *Astr. Astrophys.,* **242,** 371.
34 Elmegreen, B. G., Elmegreen, D. M. & Morris, M., 1980. *Astrophys. J.,* **240,** 455.
35 Combes, F., Encrenaz, P. J., Lucas, R. & Weliachew, L., 1977. *Astr. Astrophys.,* **61,** L7.
36 Boulanger, F., Stark, A. A. & Combes, F., 1981. *Astr. Astrophys.,* **93,** L1.
37 Rowan-Robinson, M., Phillips, T. G. & White, G., 1980. *Astr.*

Astrophys., **82,** 381.
38 Wilson, C. D. & Scoville, N., 1989. *Astrophys. J.*, **347,** 743.
39 Lord, S. D. & Young, J. S., 1990. *Astrophys. J.*, **356,** 135.
40 Morris, M. & Lo, K. Y., 1978. *Astrophys. J.*, **223,** 803.

H I data references

1 Unwin, S. C., 1980. *Mon. Not. R. astr. Soc.*, **190,** 551. Unwin, S. C., 1980. *Mon. Not. R. astr. Soc.*, **192,** 243.
2 Newton, K., 1980. *Mon. Not. R. astr. Soc.*, **190,** 689.
3 Rogstad, D. H., Wright, M. C. H. & Lockhart, I. A., 1976. *Astrophys. J.*, **204,** 703.
4 Gouguenheim, L., 1969. *Astr. Astrophys.*, **3,** 281.
5 Shostak, G. S., 1973. *Astr. Astrophys.*, **24,** 411.
6 Rogstad, D. H. & Shostak, G. S., 1972. *Astrophys. J.*, **176,** 315.
7 Bosma, A., 1978. *PhD thesis,* University of Groningen.
8 Bosma, A., van der Hulst, J. M. & Sullivan, W. T., 1977. *Astr. Astrophys.*, **57,** 373.
9 Oort, J. H., 1974. *IAU Symp. No. 58,* p. 375, ed. Shakeshaft, J. R., Reidel, Dordrecht.
10 Rogstad, D. H., Lockhart, I. A. & Wright, M. C. H., 1974. *Astrophys. J.*, **193,** 309.
11 Kaufman, M., Bash, F. N., Hine, B., Rots, A. H., Elmegreen, D. M. & Hodge, P. W., 1989. *Astrophys. J.*, **345,** 674.
12 Bosma, A., Goss, W. M. & Allen, R. J., 1981. *Astr. Astrophys.*, **93,** 106.
13 Rogstad, D. H. & Shostak, G. S., 1971. *Astr. Astrophys.*, **13,** 99.
14 Rogstad, D. H., Shostak, G. S. & Rots, A. H., 1973. *Astr. Astrophys.*, **22,** 111.
15 Tacconi, L. J. & Young, J. S., 1986. *Astr. J.*, **308,** 600.
16 Newton, K., 1980. *Mon. Not. R. astr. Soc.*, **191,** 615.
17 Rots, A. H. & Shane, W. W., 1975. *Astr. Astrophys.*, **45,** 25.
18 Rogstad, D. H., Crutcher, R. M. & Chu, K., 1979. *Astrophys. J.*, **229,** 509.
19 Allsopp, N. J., 1979. *Mon. Not. R. astr. Soc.*, **188,** 765.
20 Gottesman, S. T. & Weliachew, L., 1977. *Astr. Astrophys.*, **61,** 523.
21 Shane, W. W., 1975. In: *La Dynamique des Galaxies Spirales,* p. 217, ed. Weliachew, L., Centre National de la Recherche Scientifique, Paris.
22 Huchtmeier, W. K., 1975. *Astr. Astrophys.*, **45,** 529.
23 Combes, F., Gottesman, S. T. & Weliachew, L., 1977. *Astr. Astrophys.*, **59,** 181.
24 Huchtmeier, W. K. & Bohnenstengel, H. D., 1981. *Astr. Astrophys.*, **100,** 72.
25 Weliachew, L. & Gottesman, S. T., 1973. *Astr. Astrophys.*, **24,** 59.
26 Rots, A. H., Bosma, A., van der Hulst, J. M., Athanassoula, E. & Crane, P. C., 1990. *Astr. J.*, **100,** 387.
27 Carignan, C. & Puche, D., 1990. *Astr. J.*, **100,** 394.
28 Tully, R. B., 1974. *Astrophys. J. Suppl.*, **27,** 415.
29 Comte, G., Monnet, G. & Rosado, M., 1979. *Astr. Astrophys.*, **72,** 73.
30 Gordon, K. J., Remage, N. H. & Roberts, M. S., 1968. *Astrophys. J.*, **154,** 845.
31 Bosma, A., 1981. *Astr. J.*, **86,** 1825.
32 Emerson, D. T., 1976. *Mon. Not. R. astr. Soc.*, **176,** 321.
33 Rots, A. H., 1980. *Astr. Astrophys. Suppl.*, **41,** 189.
34 van Woerden, H., Bosma, A. & Mebold, U., 1975. In: *La Dynamique des Galaxies Spirales,* pp. 483, 285, ed. Weliachew, L., Centre National de la Recherche Scientifique, Paris.
35 Allen, R. J., 1975. In: *La Dynamique des Galaxies Spirales,* p. 157, ed. Weliachew, L., Centre National de la Recherche Scientifique, Paris.
36 Sofue, Y. & Kato, T., 1981. *Publs astr. Soc. Pacif.*, **33,** 449. Nakai, N. & Sofue, Y., 1982. *Publs astr. Soc. Japan,* **34,** 199.
37 Puche, D., Carignan, C. & Wainscoat, R. J., 1991. *Astr. J.*, **101,** 447.
38 Puche, D., Carignan, C. & Gorkom, J. H., 1991. *Astr. J.*, **101,** 456.

APPENDIX B: REFERENCES FOR TABLE 2

1 Webster, B. L. & Smith, M. G., 1983. *Mon. Not. R. astr. Soc.*, **204,** 743.
2 Graham, J. A., 1981. *Astrophys. J.*, **252,** 474.
3 de Vaucouleurs, G. & Freeman, K. C., 1972. *Vistas Astr.*, **14,** 163.
4 de Vaucouleurs, G., 1978. *Astrophys. J.*, **223,** 730.
5 Baade, W. & Swope, H. H., 1963. *Astrophys. J.*, **68,** 435.
6 Pellet, A., Astier, N., Viale, A., Courtès, G., Maucherat, A., Monnet, G. & Simien, F., 1978. *Astr. Astrophys. Suppl.*, **31,** 439.
7 Simien, F., Athanassoula, E., Pellet, A., Monnet, G., Maucherat, A. & Courtès, G., 1978. *Astr. Astrophys.*, **67,** 73.
8 Emerson, D. T., 1976. *Mon. Not. R. astr. Soc.*, **176,** 321.
9 Pence, W. D., 1978. *Publ. Astr. No. 14,* University of Texas. Pence, W. D., 1980. *Astrophys. J.*, **239,** 54. Pence, W. D., 1981. *Astrophys. J.*, **247,** 473.
10 de Vaucouleurs, G. & Page, J., 1962. *Astrophys. J.*, **136,** 107.
11 Deharveng, L., Caplan, J., Lequeux, J., Azzopardi, M., Breysacher, J., Tarenghi, M. & Westerlund, B., 1988. *Astr. Astrophys. Suppl.*, **73,** 407.
12 Madore, B. F., Welch, D. L., McAlary, C. W. & McLaren, R. A., 1987. *Astrophys. J.*, **320,** 26.
13 Sandage, A. & Tammann, G. A., 1981. *Revised Shapley Ames Catalogue of Bright Galaxies,* Carnegie Institution, Washington.
14 Rogstad, D. H., Crutcher, R. M. & Chu, K., 1979. *Astrophys. J.*, **229,** 509.
15 de Vaucouleurs, G., 1979. *Astrophys. J.*, **227,** 380.
16 Sandage, A., 1962. In: *Problems of Extragalactic Research, IAU Symp. No. 15,* p. 354, ed. McVittie, G., MacMillan, New York.
17 van der Kruit, P. C., 1973. *Astr. Astrophys.*, **29,** 231.
18 Smith, H. E., 1975. *Astrophys. J.*, **199,** 591.
19 Searle, L., 1971. *Astrophys. J.*, **168,** 327.
20 Newton, K., 1980. *Mon. Not. R. astr. Soc.*, **190,** 689.
21 Warner, P. J., Wright, M. C. H. & Lockhart, I. A., 1976. *Astrophys. J.*, **204,** 703.
22 Mayall, N. U. & Aller, L. H., 1942. *Astrophys. J.*, **95,** 5.
23 Rogstad, D. H., Wright, M. C. H. & Baldwin, J. E., 1973. *Mon. Not. R. astr. Soc.*, **163,** 16.
24 Lohmann, W., 1974. *Astrophys. Space Sci.*, **29,** 61.
25 McCall, M. L., 1982. *PhD thesis,* University of Texas, Austin. McCall, M. L., Rybski, P. M. & Shields, G. A., 1985. *Astrophys. J Suppl.*, **57,** 1.
26 Briggs, F. H., Wolfe, A. M., Krumm, N. & Salpeter, E. E., 1980. *Astrophys. J.*, **238,** 510.
27 de Vaucouleurs, G. & Peters, W. L., 1981. *Astrophys. J.*, **248,** 395.
28 Marcelin, M., 1979. *C. r. Acad. Sci. Ser. B.*, **189,** 29.
29 de Vaucouleurs, G., de Vaucouleurs, A. & Corwin, H. G., Jr, 1976. *Second Reference Catalogue of Bright Galaxies,* University of Texas Press, Austin (RC2).
30 Carranza, G. J. & Aguero, E. L., 1974. *Observatory,* **94,** 7.
31 Jorsater, S., Lindblad, P. O. & Boksenberg, A., 1984. *Astr. Astrophys.*, **140,** 288.
32 Sandqvist, Aa., Jorsater, S. & Lindblad, P. O., 1982. *Astr. Astrophys.*, **110,** 336.
33 Wright, R. R., 1969. *Publs astr. Soc. Pacif.*, **81,** 51.
34 Lindblad, P. O., 1978. In: *Astronomical papers dedicated to Bengt Strömgren,* p. 403, eds Reiz, A. & Andersen, T., Copenhagen University Observaory.
35 de Vaucouleurs, G., 1973. *Astrophys. J.*, **181,** 31.
36 de Vaucouleurs, G., 1978. *Astrophys. J.*, **224,** 710.
37 Sandage, A. R., 1962. In: *Problems of Extragalactic Research, IAU Symp. No. 15,* p. 359, ed. McVittie, G., MacMillan, New York.
38 Tammann, G. A. & Sandage, A. R., 1968. *Astrophys. J.*, **151,** 825.
39 Zaritsky, D., Elston, R. & Hill, J. M., 1990. *Astr. J.*, **99,** 1108.
40 Shostak, G. S., 1973. *Astr. Astrophys.*, **24,** 411.
41 Rogstad, D. H., Rougoor, G. W. & Whiteoak, J. B., 1967. *Astrophys. J.*, **150,** 9.
42 Deharveng, J. M. & Pellet, A., 1970. *Astr. Astrophys.*, **7,** 210.

43 Simkin, S. M., 1975. *Astrophys. J.,* **199,** 591.
44 Peterson, C. J., 1978. *Astrophys. J.,* **226,** 75.
45 de Vaucouleurs, G., 1979. *Astrophys. J.,* **227,** 739.
46 Humphreys, R. M., Aaronson, M., Lebofsky, M., McAlary, C. W., Strom, S. E. & Capps, R. W., 1986. *Astr. J.,* **91,** 808.
47 Sandage, A., 1984. *Astr. J.,* **89,** 621.
48 Rots, A. H., 1974. *PhD thesis,* University of Groningen.
49 Danver, C., 1942. *Ann. Obs. Lund.,* No. 10, 1.
50 McCall, M. L., Shields, G. A. & Rybski, P. M., 1981. *Publs astr. Soc. Pacif.,* **93,** 273.
51 de Vaucouleurs, G. 1979. *Astrophys. J.,* **227,** 729.
52 Heidmann, J., Heidmann, N. & de Vaucouleurs, G., 1971. *Mem. R. astr. Soc.,* **75,** 85.
53 Roberts, M. S., 1968. *Astr. J.,* **73,** 945.
54 Peterson, C. J., Rubin, V. C., Ford, W. K. & Thonnard, N., 1976. *Astrophys. J.,* **208,** 662.
55 van der Kruit, P. C., 1973. *Astrophys. J.,* **186,** 807.
56 Rubin, V. C., Ford, W. K. & Thonnard, N., 1980. *Astrophys. J.,* **238,** 471.
57 Crillon, R. & Monnet, G., 1969. *Astr. Astrophys.,* **1,** 449.
58 Bosma, A., van der Hulst, J. M. & Sullivan, W. T., III, 1977. *Astr. Astrophys.,* **57,** 373.
59 Bosma, A., 1978. *PhD dissertation,* University of Groningen.
60 Sandage, A. & Tammann, G. A., 1975. *Astrophys. J.,* **196,** 313.
Sandage, A. & Tammann, G. A., 1976. *Astrophys. J.,* **210,** 7.
61 Tully, R. B., 1974. *Astrophys. J. Suppl.,* **27,** 437.
62 Tammann, G. A. & Sandage, A., 1973. Private communication to ref 63.
63 Rogstad, D. H., Lockhar, I. A. & Wright, M. C. H., 1974. *Astrophys. J.,* **193,** 309.
64 Deul, E. R. & van der Hulst, J. M., 1987. *Astr. Astrophys. Suppl.,* **67,** 509.
65 Rayo, J. F., Peimbert, M. & Torres-Peimbert, S., 1982. *Astrophys. J.,* **255,** 1.
66 Bottinelli, L. & Gouguenheim, L., 1976. *Astr. Astrophys.,* **51,** 275.
67 Israel, F. P., Goss, W. M. & Allen, R. J., 1975. *Astr. Astrophys.,* **40,** 421.
68 Rogstad, D. H. & Shostak, G. S., 1972. *Astrophys. J.,* **176,** 315.
69 Bosma, A., Goss, W. M. & Allen, R. J., 1981. *Astr. Astrophys.,* **93,** 106.
70 Puche, D. & Carignan, C., 1988. *Astr. J.,* **95,** 1025 (and references therein).
71 Rogstad, D. H., Shostak, G. S. & Rots, A. H., 1973. *Astr. Astrophys.,* **22,** 111.
72 Davoust, E. & de Vaucouleurs, G., 1980. *Astrophys. J.,* **242,** 30.
73 de Vaucouleurs, G. & Davoust, E., 1980. *Astrophys. J.,* **239,** 783.
74 Baker, J. R., Haslam, C. G. T., Jones, B. B. & Wielebinski, R., 1977. *Astr. Astrophys.,* **59,** 261.
75 de Vaucouleurs, G., 1975. In: *Stars and Stellar Systems,* Vol. 9, p. 557, eds Sandage, A., Sandage, M. & Kristian, J., University of Chicago Press, Chicago.
76 Newton, K., 1980. *Mon. Not. R. astr. Soc.,* **191,** 169.
77 Allsopp, N. J., 1979. *Mon. Not. R. astr. Soc.,* **188,** 765.
78 van den Bergh, S. & Humphreys, R. M., 1979. *Astr. J.,* **84,** 604.
79 Humphreys, R. M., 1986. *Astrophys. J.,* **238,** 65.
80 Gottesman, S. T. & Weliachew, L., 1977. *Astr. Astrophys.,* **61,** 523.
81 Hodge, P. W., 1978. *Astrophys. J. Suppl.,* **37,** 429.
82 Hunter, D. A., 1982. *Astrophys. J.,* **260,** 81.
83 Helou, G., Giovanardi, C., Salpeter, E. E. & Krumm, N., 1981. *Astrophys. J. Suppl.,* **46,** 267.
Helou, G., Hoffman, G. L. & Salpeter, E. E., 1984. *Astrophys. J. Suppl.,* **55,** 433.
84 Burbidge, E. M., Burbidge, G. R. & Prendergast, K. H., 1960. *Astrophys. J.,* **132,** 640.
85 Hummel, E., Dettmar, R.-J. & Wielebinski, R., 1986. *Astr. Astrophys.,* **166,** 97.
86 Pritchet, C. J., Richer, H. B., Schade, D., Crabtree, D. & Yee, H. K. C., 1987. *Astrophys. J.,* **323,** 79.
87 Puche, D., Carignan, C. & Wainscoat, R. J., 1991. *Astr. J.,* **101,** 447.